

# Environmental Technology Verification Report

Physical Removal of Microbiological  
and Particulate Contaminants in  
Drinking Water

Ionics  
UF-1-7T Ultrafiltration Membrane  
System  
Escondido, California

Prepared by



NSF International

Under a Cooperative Agreement with



U.S. Environmental Protection Agency

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# THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM



U.S. Environmental Protection Agency



NSF International

## ETV Joint Verification Statement

TECHNOLOGY TYPE:	<b>MEMBRANE FILTRATION USED IN PACKAGED DRINKING WATER TREATMENT SYSTEMS</b>		
APPLICATION:	<b>PHYSICAL REMOVAL OF MICROBIOLOGICAL &amp; PARTICULATE CONTAMINANTS IN DRINKING WATER IN ESCONDIDO, CALIFORNIA</b>		
TECHNOLOGY NAME:	<b>UF-1-7T ULTRAFILTRATION MEMBRANE SYSTEM</b>		
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The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV program is to further environmental protection by substantially accelerating the acceptance and use of improved and more cost-effective technologies. ETV seeks to achieve this goal by providing high quality, peer reviewed data on technology performance to those involved in the design, distribution, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations; stakeholders groups which consist of buyers, vendor organizations, and permittees; and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

NSF International (NSF) in cooperation with the EPA operates the Drinking Water Treatment Systems (DWTS) Pilot, one of 12 technology areas under ETV. The DWTS Pilot recently evaluated the performance of an ultrafiltration membrane system used in package drinking water treatment system applications. This verification statement provides a summary of the test results for the Ionics UF-1-7T Ultrafiltration (UF) Membrane System. Montgomery Watson, an NSF-qualified field testing organization (FTO), performed the verification testing.

## **ABSTRACT**

Verification testing of the Ionics UF-1-7T Ultrafiltration membrane system was conducted over two test periods at the Aqua 2000 Research Center in Escondido, California. The first test period, from December 7, 1999 to January 11, 2000 represented winter conditions. The second test period, from March 6, 2000 to April 6, 2000 represented spring conditions. The source water was a blend of Colorado River and State Project Water. Verification testing was conducted at manufacturer specified operating conditions. The membrane unit was operated in dead-end mode at a constant flux of 33 gfd (57 L/hr-m<sup>2</sup>) with feedwater recovery of 92-93 percent. Test Period 1 consisted of one filtration run. The membrane was completely fouled at the end of Test Period 1. Between test periods, modifications were made to the backwash protocol. As a result, the system completed Test Period 2 without appreciable loss of specific flux. The system experienced one incident of fiber breakage during Test Period 1 and three incidents of fiber breakage in Test Period 2. The manufacturer recommended cleaning procedure was effective in recovering membrane productivity. The membrane system achieved significant removal of particulate contaminants and bacteria and seeded MS2 bacteriophage as described later.

## **TECHNOLOGY DESCRIPTION**

The Ionics UF-1-7T unit is comprised of seven hollow fiber UF membrane modules inside an aluminum pressure vessel and mounted on a transportable skid. The skid is constructed of steel, and can be shipped by truck. The Ionics UF unit is completely self-contained, including all the components required for operation. The only connections are a raw water connection to the feed pump, drain lines for filtrate tank overflow and backwash waste, and electrical power. The unit requires approximately 35 ft<sup>2</sup> (3.2 m<sup>2</sup>) of floor space.

The UF-1-7T unit has an Allen Bradley programmable logic controller (PLC). The PLC controls the opening and closing of pneumatic valves and the operation of pumps required for filtration and backwash. The backwash frequency and the length of time the system spends in each backwash phase are set by entering values into the appropriate screen on the PLC. The PLC maintains a constant filtrate flow during filtration by automatically adjusting feed pump speed. The Ionics UF unit has digital flow, pressure and temperature measurement and a data logger to acquire operating information digitally.

The Ionics UF-1-7T unit has two alternating operating modes. These are filtration and backwash. During filtration, raw water is driven under pressure through pores in the UF membrane. Treated water is collected from the filtrate side (inside) of the membrane. At the end of the filtration cycle, the system initiates a backwash. During backwash, the feed pump shuts down, valves are repositioned, and the backwash pump starts. The backwash pump draws treated water from the filtrate storage tank, chlorinates it, and forces the water under pressure in the reverse direction through the fibers. This reverse flow removes solids and organics, which have accumulated on the membrane surface. Chlorine is added to the backwash water to assist in oxidizing organics that have accumulated on the membrane surface. Air is also added during backwashing to scour the membrane for more effective cleaning. The long-term operation of the Ionics UF unit frequently results in the accumulation of materials on the membrane surface which are not effectively removed by backwash. This is called membrane fouling and is quantified by a gradual increase in the pressure required to maintain the desired flux. Once a critical upper pressure has been reached, normal operation is discontinued and the membrane undergoes chemical cleaning. Chemical cleaning involves the use of a citric acid solution, followed by a high pH solution and pH 2 backwash to restore membrane productivity.

The pressure vessel of the Ionics UF unit contains seven Toray Model TP-TE07-S membrane modules. These 3.5 inch (8.8 cm) diameter modules each contain approximately 3,600 fibers. The Toray module is a

hollow fiber configuration, manufactured from polyacrylonitrile, with nominal molecular weight cut-off of 100,000 Daltons. This corresponds with a pore diameter of approximately 0.01 micron. At this pore size, the membrane is expected to remove particulates, including protozoa, bacteria and virus.

## **VERIFICATION TESTING DESCRIPTION**

### ***Test Site***

The verification test site was the City of San Diego's Aqua 2000 Research Center at 14103 Highland Valley Road in Escondido, California. The Research Center includes office and lab trailers, a covered concrete test pad and a dedicated operations staff with substantial membrane experience. The source water for testing was Lake Skinner water via the San Diego Aqueduct. Lake Skinner water consists of Colorado River water and State Project water, which are two of the major raw drinking water supplies in Southern California.

### ***Methods and Procedures***

Turbidity, pH, chlorine and temperature analyses were conducted daily at the test site according to Standard Methods for the Examination of Water and Wastewater, 19<sup>th</sup> Ed. (APHA, et. al., 1995). Standard Methods, 19<sup>th</sup> Ed. (APHA, 1995) and Methods for Chemical Analysis of Water and Wastes (EPA, 1979) were used for analyses conducted at The City of San Diego Laboratory. These included alkalinity, total and calcium hardness, total dissolved solids (TDS), total suspended solids (TSS), total organic carbon (TOC), ultraviolet absorbance at 254 nanometers (UV254), total coliform and heterotrophic plate count (HPC). Total and calcium hardness analyses were conducted every other week. All other analyses were conducted weekly. MS2 bacteriophage analysis was conducted by EPA Information Collection Rule (ICR) Method for Coliphage Analysis (Sobsey, et al. 1990). Online Hach 1900 WPC particle counters and 1720D turbidimeters continuously monitored these parameters in both the raw water and membrane system filtrate. The particle counters were set up to enumerate particle counts in the following size ranges: 2-3  $\mu\text{m}$ , 3-5  $\mu\text{m}$ , 5-7  $\mu\text{m}$ , 7-10  $\mu\text{m}$ , 10-15  $\mu\text{m}$  and  $> 15 \mu\text{m}$ . Data from the online particle counters and turbidimeters were stored at one-minute intervals on a computer.

## **VERIFICATION OF PERFORMANCE**

### ***System Operation***

Verification testing was conducted at manufacturer specified operating conditions. The membrane unit was operated at a constant flux of 33 gfd (57 L/hr-m<sup>2</sup>) with feedwater recovery of 92 percent. Filtrate flow rate was set by entering the target flow in a screen on the PLC. Backwash frequency was every 60 minutes. Backwash volume averaged 55 gallons (208 liters) for Test Period 1 and 75 gallons (283 liters) for Test Period 2. Backwash chlorine concentration was in the range 5 to 10 mg/L. The reverse flow backwash volume was increased from 15 gallon (57 liters) in Test Period 1 to 30 gallon (113 liters) in Test Period 2. The system was operated during Test Period 1 with moderate fouling until it reached the maximum recommended operating pressure towards the end of the testing period. During this period specific flux decreased from 6.0 to 1.2 gfd/psi at 20°C (148 to 39 L/hr-m<sup>2</sup> at 20°C). The system, however, ran all of Test Period 2 without appreciable fouling. During Test Period 2 the specific flux decreased from 5.9 gfd/psi at 20°C (145 L/hr-m<sup>2</sup> at 20°C) over three days before stabilizing at 4.0 gfd/psi at 20°C (98 L/hr-m<sup>2</sup> at 20°C) for remainder of testing.

Membrane cleaning was performed according to manufacturer recommended procedure. A citric acid solution followed by a high pH cleaning solution was prepared in the feed storage tank and recirculated through the feed side of the membrane at approximately 330 gpm (1250 L/min) for 60 minutes. A pH 2 acid rinse was used after the high-pH cleaning step to remove potential precipitates. Flux-pressure profiles

were performed after each cleaning step to evaluate recovery of specific flux. The manufacturer recommended cleaning procedure was effective in recovering specific flux. Loss of original flux was 4.8 percent after the cleaning at the end of Test Period 1 and 17 percent after the cleaning at the end of Test Period 2.

One incident of broken fibers occurred during Test Period 1 and three incidents of broken fibers occurred during Test Period 2. Air pressure-hold tests were conducted near the beginning and end of each test period as well as before and after fiber repairs to assess membrane integrity. Air pressure-hold tests were conducted by selecting the integrity test from the appropriate PLC screen. During the air pressure-hold test the pressure vessel is first drained, then the feed side of the membrane is pressurized with air and the filtrate side of the membrane is opened to atmosphere. Once pressurized, the loss of held pressure on the feed side was monitored over 10 minutes. A loss of > 1 psi every five minutes of held pressure typically would indicate the membranes were not intact. The air pressure-hold test was inconsistent in identifying fiber breaks based on this performance criterion. The pressure decay before repair was less than 2 psi for two fiber breakages and just over 2 psi for the other two fiber breakage incidents. Particle counting was a reliable indicator of broken fibers, and all incidents of broken fibers were identified by visual observation of filtrate particle counts. Typically, one or two broken fibers produced a increase in permeate particle counts (> 2 um) of from one-half to one log.

### **Source Water**

The source water for the ETV testing consisted of a blend of Colorado River water and State Project water delivered to the test site via the San Diego Aqueduct. The source water had the following average water quality during the two test periods: TDS 500/470 mg/L, total hardness 240/220 mg/L as CaCO<sub>3</sub>, alkalinity 120/120 mg/L as CaCO<sub>3</sub>, TOC 3.2/3.6 mg/L, pH 8.3/8.2, temperature 15/19 °C and turbidity 1.2/1.4 NTU.

### **Particle Removal**

Total suspended solids in the filtrate were removed to below the detection limit for the analysis (1 mg/L), for all samples analyzed. Filtrate turbidity was 0.05 NTU or less 95 percent of the time. The test system removed greater than 3 logs of both Cryptosporidium-sized (3-5 um) particles and Giardia-sized (5-15 um) particles, 95 percent of the time. Filtrate levels of particles in these size ranges were elevated and particle removal was decreased during periods of operation with compromised fibers that occurred during Test Period 2. Four hour average raw water and filtrate particle levels and daily average particle removal in these size ranges for Test Periods 1 and 2 are presented in the following table:

<b>Ionics UF-1-7T UF System Particle Counts and Particle Removals for Test Periods 1/2</b>						
	3-5 um Particles			5-15 um Particles		
	Raw Water (#/mL)	Filtrate (#/mL)	Log Removal	Raw Water (#/mL)	Filtrate (#/mL)	Log Removal
Average	1700/1400	0.19/0.63	4.2/3.4	900/680	0.16/0.37	3.9/3.3
Standard Deviation	230/310	0.35/0.46	0.40/0.30	170/200	0.26/0.24	0.40/0.24
95% Confidence Interval	1700-1700/	0.14-0.24/	4.1-4.3/	880-920/	0.12-0.20/	3.8-4.0/
	1400-1400	0.56-0.70	3.3-3.5	650-710	0.34-0.40	3.2-3.4
Minimum	1200/690	0.04/0.15	3.0/2.9	530/270	0.04/0.11	3.0/2.8
Maximum	2300/2400	1.7/3.4	4.6/3.9	1400/1500	1.9/2.3	4.4/3.7

### **Microbial Removal**

Total Coliforms and HPC were analyzed on a weekly basis during both ETV test periods. Raw water total coliforms averaged 25 and 8 MPN/100mL during Test Periods 1 and 2, respectively. No total coliforms

were detected in the filtrate. HPC averaged 83 and 310 cfu/mL in the raw water for Test Periods 1 and 2 while filtrate levels of HPC averaged 100 and 200 cfu/mL, respectively. The relatively high levels of HPC in the filtrate are possibly due to contamination of the filtrate side with HPC during periods of operation with compromised fibers. Challenge experiments with MS2 bacteriophage were conducted at the end of Test Period 1 and beginning of Test Period 2, immediately after membrane cleaning (worst case for virus removal). Virus were continuously added to the membrane feed water. The membrane was allowed to operate for 1 filtration cycle to come to equilibrium and then paired samples were taken from the feed and filtrate within 1-minute of completion of backwash, at the middle and at the end of the filtration cycle, over the next two filtration cycles. Specific flux during the seeding conducted at the end of Test Period 1 was 4.9 gfd/psi (119 L/hr-m<sup>2</sup>-bar), while specific flux for the seeding conducted at the beginning of Test Period 2 was 6.2 gfd/psi (152 L/hr-m<sup>2</sup>-bar). Feed virus concentration ranged from 7.4 x 10<sup>6</sup> to 2.8 x 10<sup>7</sup> plaque forming units (pfu)/100mL for the first virus seeding and from 3.5 x 10<sup>7</sup> to 6.0 x 10<sup>7</sup> pfu/100mL for the second virus seeding. Log removal of virus ranged from 4.0 to 5.7 for Test Period 1 and from 2.9 to 4.3 for Test Period 2.

### ***Operation and Maintenance Results***

Operation was initiated by entering target filtrate flow rate, backwash frequency and time of each backwash phase in the appropriate PLC screen. Backwash flow rate was adjusted manually using a valve. As the membrane system fouled, the feed pump speed was automatically readjusted to maintain a constant filtrate flow rate. The sodium hypochlorite dosing pump required initial manual adjustment to achieve a target chlorine dose in the backwash water of 5 to 10 mg/L. Chlorine concentration in the backwash feedwater was checked twice daily.

Operation of the membrane unit consumed 0.12 gal (0.46 L) of 10% sodium hypochlorite per day to chlorinate backwash water. No other chemicals were consumed during routine operation of the system. During a typical chemical cleaning, 17.0 pounds (7.7 kg) of citric acid, 1.8 gallon (7.0 liter) of high pH cleaning solution and 200 milliliters of muriatic acid (40% hydrochloric acid) were consumed. The manufacturer supplied an Operations and Maintenance manual that was extremely helpful in explaining the setup, operation and maintenance of the ETV test system.

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**Availability of Supporting Documents**

Copies of the *ETV Protocol for Equipment Verification Testing for Physical Removal of Microbiological and Particulate Contaminants*, dated April 20, 1998 and revised May 14, 1999, the Verification Statement, and the Verification Report (NSF Report #00/13/EPADW395) are available from the following sources:

(NOTE: Appendices are not included in the Verification Report. Appendices are available from NSF upon request.)

Drinking Water Systems ETV Manager (order hard copy)

NSF International

P.O. Box 130140

Ann Arbor, Michigan 48113-0140

NSF web site: <http://www.nsf.org/etv> (electronic copy)

EPA web site: <http://www.epa.gov/etv> (electronic copy)

September 2000

## **Environmental Technology Verification Report**

### **Physical Removal of Microbiological and Particulate Contaminants in Drinking Water**

#### **Ionics UF-1-7T Ultrafiltration Membrane System Escondido, California**

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## **Notice**

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## **Foreword**

The following is the final report on an Environmental Technology Verification (ETV) test performed for the NSF International (NSF) and the United States Environmental Protection Agency (EPA) by Montgomery Watson, in cooperation with Ionics. The test was conducted in 1999 and 2000 at the Aqua 2000 Research Center in San Diego, California.

Throughout its history, the EPA has evaluated the effectiveness of innovative technologies to protect human health and the environment. The ETV Program has been instituted to verify the performance of innovative technical solutions to environmental pollution or human health threats. ETV was created to substantially accelerate the entrance of new environmental technologies into the domestic and international marketplace. Verifiable, high quality data on the performance of new technologies are made available to regulators, developers, consulting engineers, and those in the public health and environmental protection industries. This encourages more rapid availability of approaches to better protect the environment.

The EPA has partnered with NSF, an independent, not-for-profit testing and certification organization dedicated to public health, safety and protection of the environment, to verify performance of small drinking water systems that serve small communities under the ETV Drinking Water Treatment Systems (DWTS) Pilot Project. A goal of verification testing is to enhance and facilitate the acceptance of small drinking water treatment equipment by state drinking water regulatory officials and consulting engineers while reducing the need for testing of equipment at each location where the equipment's use is contemplated. NSF will meet this goal by working with manufacturers and NSF-qualified Field Testing Organizations (FTO) to conduct verification testing under the approved protocols.

NSF is conducting the ETV DWTS with participation of manufacturers, under the sponsorship of the EPA Office of Research and Development, National Risk Management Research Laboratory, Water Supply and Water Resources Division, Cincinnati, Ohio. It is important to note that verification of the equipment does not mean that the equipment is "certified" by NSF or "accepted" by EPA. Rather, it recognizes that the performance of the equipment has been determined and verified by these organizations for those conditions tested by the FTO.

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- Appendix B – Raw Data Sheets
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## Abbreviations and Acronyms

C	Celsius degrees	mg/L	Milligram(s) per liter
cfu	Colony forming unit(s)	min	Minute(s)
CIP	Clean in place	mL	Milliliter(s)
C <sub>f</sub>	Feed concentration	MPN	Most probable number
C <sub>p</sub>	Filtrate concentration	NIST	National Institute of Standards and Technology
cm	Centimeter	NSF	NSF International (formerly known as the National Sanitation Foundation)
CRW	Colorado River water	NTU	Nephelometric turbidity unit(s)
d	Day(s)	O&M	Operations and Maintenance
DI	Deionized	P <sub>i</sub>	Pressure at inlet of membrane module
DOC	Dissolved organic carbon	P <sub>o</sub>	Pressure at outlet of membrane module
DWTS	Drinking Water Treatment System	P <sub>p</sub>	Filtrate pressure
EPA	Environmental Protection Agency	P <sub>tm</sub>	Transmembrane pressure
ETV	Environmental Technology Verification	PC	Personal computer
FOD	Field Operations Document	PLC	Programmable Logic Controller
ft <sup>2</sup>	Square foot (feet)	ppm	Parts per million
FTO	Field Testing Organization	psi	Pound(s) per square inch
gfd	Gallon(s) per day per square foot of membrane area	PVC	Polyvinyl chloride
gpd	gallon per day	Q <sub>f</sub>	Feed flow
gpm	Gallon(s) per minute	Q <sub>p</sub>	Filtrate flow
HPC	Heterotrophic plate count	Q <sub>r</sub>	Recycle flow
hr	Hour(s)	QA	Quality assurance
ICR	Information Collection Rule	QC	Quality control
in Hg	Inch(es) of Mercury	S	Membrane surface area
J <sub>Si</sub>	Initial specific transmembrane flux	scfm	Standard cubic feet per minute
J <sub>Sf</sub>	Final specific transmembrane flux	slpm	Standard liter per minute
J <sub>S</sub>	Specific flux	sec	Second(s)
J <sub>Si0</sub>	Initial specific transmembrane flux at t=0 of membrane operation	SPW	State Project water
J <sub>t</sub>	Filtrate flux	T	Temperature
J <sub>tm</sub>	Transmembrane flux	TC	Total coliform bacteria
kg	Kilogram(s)	TOC	Total organic carbon
L	Liter(s)	TDS	Total dissolved solids
m <sup>2</sup>	Square meter(s)	TSS	Total suspended solids
m <sup>3</sup> /d	Cubic meter(s) per day	um	Micron(s)
mgd	Million gallons per day	UF	Ultrafiltration
		UV254	Ultraviolet light absorbance at 254 nanometer

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## **Chapter 1**

### **Introduction**

#### **1.1 Environmental Technology Verification (ETV) Purpose and Program Operation**

The U.S. Environmental Protection Agency (EPA) has created the ETV Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV program is to further environmental protection by substantially accelerating the acceptance and use of improved and more cost-effective technologies. ETV seeks to achieve this goal by providing high quality, peer reviewed data on technology performance to those involved in the design, distribution, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations; stakeholders groups which consist of buyers, vendor organizations, and permittees; and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory testing (as appropriate), collecting and analyzing data, and preparing peer reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

NSF International (NSF) in cooperation with the EPA operates the Drinking Water Treatment Systems (DWTS) Pilot, one of 12 technology areas under ETV. This DWTS Pilot evaluated the performance the Ionics UF-1-7T ultrafiltration (UF) system used in drinking water treatment system applications.

This report provides the ETV results for the Ionics UF-1-7T membrane system.

#### **1.2 Project Participants**

Figure 1-1 is an organization chart showing the project participants and the lines of communication established for the ETV. The Field Testing Organization (FTO) was Montgomery Watson, a NSF-qualified FTO, which provided the overall management of the ETV through the project manager and project engineer. The ultrafiltration membrane manufacturer for the ETV was Ionics. The operations management and staff were from the test site at the City of San Diego Metropolitan Wastewater Department, Aqua 2000 Research Center in Escondido, California. The City of San Diego laboratory, a State-certified laboratory, provided water quality analyses. Data management and final report preparation were performed by the FTO, Montgomery Watson.

#### **1.3 Definition of Roles and Responsibilities of Project Participants**

##### ***1.3.1 Field Testing Organization Responsibilities***

The specific responsibilities of the FTO, Montgomery Watson, were to:

- Provide the overall management of the ETV through the project manager and the project engineers.
- Provide all needed logistical support, the project communication network, and all scheduling and coordination of the activities of all participants.
- Manage, evaluate, interpret and report on data generated in the ETV.
- Evaluate the performance of the ultrafiltration membrane technology according to the Field Operating Document (FOD) and the testing, operations, quality assurance/quality control (QA/QC), data management and safety protocols contained therein.
- Provide all quality control (QC) information in the ETV report.
- Provide all data generated during the ETV in hard copy and electronic form in a common spreadsheet or database format.

### ***1.3.2 Manufacturer Responsibilities***

The specific responsibilities of the ultrafiltration membrane manufacturer, Ionics, were to:

- Provide complete, field-ready equipment for the ETV at the testing site.
- Provide logistical and technical support as required throughout the ETV.
- Provide partial funding for the project.
- Attend project meetings as necessary.

### ***1.3.3 Operator and Test Site Staff Responsibilities***

The specific responsibilities of the operations and test site staff from the City of San Diego Metropolitan Wastewater Department were to:

- Provide set-up, shake-down, operations, maintenance and on-site analytical services according to the FOD and the testing, operations, QA/QC, data management and safety protocols.
- Provide the necessary and appropriate space for the equipment to be tested in the ETV.
- Provide all necessary electrical power, feedwater and other utilities as required for the ETV.
- Provide all necessary drains to the test site.

### ***1.3.4 Water Quality Analyst Responsibilities***

The specific responsibilities of the water quality analytical staff from the City of San Diego Laboratory were to:

- Provide all off-site water quality analyses prescribed in the FOD according to the QA/QC protocols contained therein.
- Provide reports with the analytical results to the data manager.
- Provide detailed information on the analytical procedures implemented.

### ***1.3.5 NSF Responsibilities***

NSF was responsible for administration of the testing program. Specific responsibilities of the NSF were to:

- Develop test protocols and qualify FTOs.
- Review and approve FODs.
- Conduct inspections and make recommendations based on inspections.
- Conduct financial administration of the project.
- Review all project reports and deliverables.

### ***1.3.6 EPA Responsibilities***

The specific responsibilities of EPA were to:

- Initiate the ETV program.
- Provide significant project funding.
- Review final reports.

## **Chapter 2**

### **Equipment Description and Operating Processes**

The equipment tested in the ETV is Ionics UF-1-7T package ultrafiltration membrane system. The test unit is comprised of seven membrane modules in an aluminum pressure vessel mounted on a transportable skid. The 3.5 inch (8.8 cm) diameter ultrafiltration modules are model TP-TE07-S, manufactured by Toray in Japan. The skid is constructed of steel, and can be shipped by truck. A photograph of the ETV test unit is shown in Figure 2-1. The figure shows the front of the UF-1-7T system in the photo on the left, and the back of the system (including the aluminum membrane pressure vessel) on the right. The skid includes all major equipment elements and controls and requires approximately 35 square feet (ft<sup>2</sup>) or 3.2 square meters (m<sup>2</sup>) of floor space. The Ionics UF unit is shipped with an oil-free air compressor that is used for air scour during backwash as well as for operating pneumatic valves. The spatial requirements and locations of major components and instruments of the Ionics UF unit are shown in Figure 2-2.

The Ionics UF unit is completely self-contained, including all the components required for operation. The only connections are a raw water connection to the feed pump, drain lines for filtrate tank overflow and backwash waste, and electrical power.

The Ionics UF unit includes an Allen Bradley programmable logic controller (PLC) with PanelView display. Operating parameters such as filtrate flow rate, backwash frequency and time spent in each backwash phase are set using the PLC. The PLC automatically controls feed pump speed to maintain a constant filtrate flow and controls pumps and valves during backwash.

The Ionics UF unit has two alternating operating modes: filtration and backwash. During filtration, feed water is driven under pressure from the feed side of the hollow fibers (outside of fibers), through pores in the UF membrane. Filtrate is collected from the inside of the fibers. The filtration cycle typically lasts from 15 to 30 minutes. At the end of the filtration cycle, the system initiates a backwash. During backwash, the feed pump shuts down, valves are repositioned, and the backwash pump starts. The backwash pump draws treated water from the filtrate storage tank, chlorinates it, and forces the water under pressure in the reverse direction through the fibers. With the flow of water now from the inside of the fiber to the outside of the fiber, the backwash water exits to the outside of the fibers, carrying with it particulate material which has accumulated on the membrane surface during filtration. Chlorine added to the backwash water assists in oxidizing organics that have accumulated on the membrane surface. Air is also added to the feed side during the backwashing step to scour the membrane for more effective cleaning. The backwash cycle typically lasts from 45 to 90 seconds, after which the unit returns to filtration mode. Filtrate storage tank overflow and backwash waste streams were directed to drain.

The long-term operation of the Ionics UF unit frequently results in the accumulation of materials on the membrane surface, which are not effectively removed by backwash. This is called membrane fouling and is quantified by a gradual increase in the pressure required to force water through the membrane pores. Once a critical upper pressure has been reached, normal operation is discontinued and the membrane undergoes chemical cleaning. Chemical cleaning involves the use of acid and caustic solutions to restore efficient operation of the membrane.

The Ionics UF package unit uses seven model TP-TE07-S membrane modules manufactured by Toray. Table 2-1 provides the specification of membranes used in the Ionics UF membrane system. The information in Table 2-1 is taken from a letter supplied by the system manufacturer, Ionics (see Appendix A). The Toray module is a hollow-fiber, outside-in configuration membrane with nominal molecular weight cut-off of approximately 100,000 daltons. This corresponds with a pore diameter of approximately 0.01 micron. At this pore size, the membrane is expected to remove particulate material, including protozoa, bacteria and virus.

## **2.1 Description of the Treatment Train and Unit Processes**

Figure 2-3 presents a schematic diagram of the Ionics UF system. The test system has two alternating operation modes: filtration and backwash.

The operation of the UF membrane system is summarized in the following steps:

1. The feed pump provides the pressure (up to approximately 44 pounds per square inch (psi) or 3.0 bars) needed to filter the water through the membranes at a constant flow rate. Feed pump speed is automatically adjusted to achieve the desired filtrate flow. Feed water is pumped into the base of the pressure vessel.
2. The pressure in the 45 gallon pressure vessel forces water through the pores of the membrane fibers to the inside of the fibers. The filtrate water travels up the fibers to the top of the pressure vessel, which is sealed from the feed side of the pressure vessel, and into the approximately 80 gallon (300 liter) filtrate storage tank. Overflow from the filtrate storage tank was directed to drain. The modules filter on a cycle of 15 to 30 minutes, after which a backwash is initiated.
3. Backwash is initiated automatically based on a timer. The objective of the backwash is to remove solids and organics that have accumulated on the feed side (outside) of the membrane surface during filtration. A PLC automatically operates pumps and valves to accomplish a backwash.
4. There are two distinct backwash cycles. These are referred to as “B” backwash and “C” backwash. During both Test Periods, nine “B” backwashes were performed, followed by a “C” backwash. The number of “B” backwashes before a “C” backwash is selected by entering the desired number of “B” backwashes in the appropriate screen on the PLC. The “B” backwash consisted of air scour, fast flush with feed water, and reverse flow with chlorinated filtrate. A “C” backwash consisted of fast flush with air scour, reverse flow, emptying and then refilling the pressure vessel with feed water. In an effort to reduce fouling of the system, the “B” backwash sequence was modified to include more reverse flow and less fast flush water consumption between Test Periods 1 and 2. The “B” backwash sequence from Test Period 1 is described below:
  - 4.1 Fast Flush 1. During fast flush, feed water is pumped into the bottom of the pressure vessel and exits the top of the pressure vessel removing some of the accumulated solids. This step lasts approximately 10 seconds and consumes 12 gallons of feed water.
  - 4.2 Reverse Flow. During this backwash phase, filtrate from the filtrate storage tank is pumped under pressure in the reverse direction through the membrane and exits into the pressure vessel. The backwash feed water is chlorinated to approximately 5-10

milligrams per liter (mg/L). This step lasts approximately 15 seconds and consumes 15 gallons of filtrate.

- 4.3 Air Scour. During air scour, 1 standard cubic foot per minute (scfm) or 3.8 standard liters per minute (slpm) air is introduced to the base of each module. The air flow agitates the fibers and assists in removal of accumulated solids. This step lasts approximately 20 seconds.
- 4.4 Intermediate Flush. The intermediate flush phase consists of a fast flush cycle with air scour. This cycle lasts 10 seconds and consumes 12 gallons of feed water.
- 4.5 Fast Flush 2. This final fast flush with feed water removes air from the top of the pressure vessel. This phase lasts approximately 5 seconds and consumes 7 gallons of feed water.

Overall, the “B” backwash lasted 60 seconds. Waste from the backwash cycle is routed to drain.

5. Backwash wastewater was directed to drain during ETV testing. At the completion of backwash, the PLC stops the backwash pump, readjusts the appropriate valves and restarts the system in filtration mode.

After extended periods of operation, typically on the order of weeks to months, the pressure required to force water through the membrane pores increases because some material is not effectively removed by backwash. This process is called membrane fouling. Once the system reaches a critical pressure, the system is shut down and a chemical cleaning is performed to restore membrane efficiency. The Ionics ETV test system was considered fouled when the transmembrane pressure reached a critical pressure of 15 to 20 psi (1.0 – 1.4 bar). Cleaning the Ionics unit is a two-step process. A citric acid solution with pH between 2.0 and 2.5 is used first. This is followed by a high pH (pH in the range 10 to 12) cleaning step. Finally, a pH 2 hydrochloric acid rinse is performed to remove any metals that may have precipitated on the membrane.

Each step in the cleaning process involves preparing approximately 100 gallons of cleaning solution, preheated to 35 °C, in the feed storage tank contained on the membrane system skid. The feed tank includes a heating element to maintain the cleaning solution temperature. Valves are reconfigured so the fast flush drain flow and filtrate flow are returned to the feed/cleaning tank. The feed pump is started, and the system is adjusted to recirculate cleaning solution on the feed side of the membrane at 330 gallon per minute (gpm) or 1250 liter/min, with no filtrate flow, for 60 minutes. After this, the filtrate valve is adjusted to allow a filtrate flow of 21 gpm (80 L/min), with the same concentrate flow for 15 minutes. After the cleaning step is complete, the cleaning solution is directed to drain, the filtrate storage tank is filled with tap water and the contents of the filtrate tank are backwashed through the system to remove residual cleaning solution from the membrane modules. After the high pH cleaning step, a pH 2 hydrochloric acid rinse is conducted to remove possible metal precipitates.

Filtration, in the Ionics UF unit, is accomplished with seven Model TP-TE07-S UF membrane modules manufactured by Toray. The Toray membrane is a hollow fiber configuration with fibers potted at the top only. Each fiber runs from the potting material down the inside of a clear acrylic tube. The fiber then wraps around a plastic cross pipe near the base of the acrylic tube, and runs back up the tube and the other fiber end is potted in the opposite half of the potting at the top.

Each fiber has an inside diameter of approximately 0.016 inch (0.4 mm), an outside diameter of 0.026 inch (0.68 mm) and is 5.2 feet (1.6 m) long from end to end (see Table 2-1). With approximately 3,600 fibers per module, the active surface area of each module is approximately 129 square feet (12 square meters). The membrane material is polyacrylonitrile. The surface of the membrane has a neutral charge and is hydrophilic. The membrane is chlorine tolerant, has an operating pH range of 2 – 10, and can operate to a maximum transmembrane pressure of 44 psi (3.0 bar).

The fibers hang from the potting material inside a clear acrylic cylinder that is open at the bottom and has approximately eight holes ½ inch (1.3 cm) in diameter around the top. The top of each module has two o-rings that seal the feed side of the pressure vessel below, from the filtrate side of the pressure vessel above. The modules are installed by removing the top of the pressure vessel and slipping the modules into precision-machined holes in an approximately ¾ inch (1.9 cm) thick aluminum plate.

## **2.2 Description of Physical Construction/Components of the Equipment**

The Ionics UF unit is skid-mounted with a footprint of approximately 8 feet 9 inches (2.7 m) long by 4 feet (1.2 m) deep. The unit is 7 feet 2 inches (2.2 m) in height with a base and frame constructed of steel. At a weight of 2,800 pounds (1,270 kg), including air compressor, the unit can be moved with a forklift and transported by truck. The Ionics UF unit is self contained, requiring only connections to feedwater, drain and electrical. The electrical requirements of the system are 50 amps of 480 volt three-phase, 60 Hz power.

The major components of the Ionics ETV test unit included:

- Seven 129 ft<sup>2</sup> (12 m<sup>2</sup>) Toray TP-TE07-S UF modules housed in an 18 inch (46 cm) diameter aluminum pressure vessel
- PLC-based control system
- Backwash pump
- Feed pump
- Feed storage / cleaning tank
- Filtrate storage tank
- Air compressor
- Pneumatic valves
- Sodium hypochlorite tank and metering pump
- Rotameter and magmeter flow meters
- Digital pressure gauges
- Digital feed thermometer.

Figure 2-2 presents the spatial requirements and layout of the major components of the Ionics UF unit.

## **Chapter 3**

### **Materials and Methods**

#### **3.1 Testing Site Name and Location**

The test site selected for the ETV project is the City of San Diego's Aqua 2000 Research Center at 14103 Highland Valley Road in Escondido, California.

##### ***3.1.1 Site Background Information***

The Aqua 2000 Research Center was established in 1995 to conduct most of the research work related to the Water Repurification Project of the City of San Diego. The Center has dedicated full time operators with substantial experience in operating membrane systems. This site is also connected to San Diego County Water Authority's Aqueduct System. Sufficient raw water supply, electrical power, and proper drainage lines to a wastewater treatment plant were provided to the ETV test system treatment train.

##### ***3.1.2 Test Site Description***

Figure 3-1 is a schematic diagram of the test site and the location of the Ionics UF unit. Below is a list of the facilities and equipment that were available at the test site.

#### **Structural**

- 5,000 square foot concrete pad.
- Semi-permanent shading to protect from sunlight.
- Potable water connections.
- San Diego County Water Authority's Aqueduct System connections.
- Drainage system connected to a wastewater plant.
- Chemical containment area.
- Sufficient lighting for 24-hour operation.
- Full electrical supply.
- Chemical safety shower and eyewash.
- An operations trailer with conference room, offices, and computers.
- A laboratory trailer for on-site water quality analyses.

#### **Instrumentation/Equipment**

##### ***On-Site Laboratory***

- DR 4000 Spectrophotometer by Hach
- Ratio/non-ratio 2100N Turbidimeter by Hach
- pH/Temperature meter by Accumet Research (AR-15)
- Portable conductivity meter by Fisher (No. 09-327-1)
- Two total organic carbon (TOC) Analyzers (Sievers Model No. 800)

### ***Concrete Pad***

- Feed, filtrate, backwash, and waste storage tanks.
- Chemical Cleaning Skid with hot water supply.
- Chemical Feed Systems.
- Micro 2000 On-line Chlorine Analyzer
- Four 1720D On-line Hach Turbidimeters
- Four 1900WPC On-line Hach Particle Counters

### ***Raw Water Intake***

The raw water was delivered to the test site through schedule 80 PVC pipe. The San Diego Aqueduct connection was approximately one mile away from the test site. The available water flow rate was 150 gpm.

### ***Collection of Raw Water***

The raw water was directed to a covered tank with an overflow system. The feedwater pipe of the test unit was connected to the covered raw water tank.

### ***Handling of Treated Water and Residuals***

The Aqua 2000 Research Center has a drainage system that connects to a wastewater treatment plant. All of the filtrate, backwash water, and any chemicals used were directed to waste.

## **3.2 Source/Feed Water Quality**

The source of feedwater for the ETV testing is San Diego Aqueduct Water. The aqueduct is supplied primarily from Lake Skinner which receives Colorado River Water (CRW) from the West Portal of the San Jacinto Tunnel, and State Project Water (SPW) from Lake Silverwood. A typical blending ratio of these two waters in Lake Skinner is 70 percent CRW and 30 percent SPW. The lower total dissolved solids (TDS) SPW is added to maintain the TDS of Lake Skinner at approximately 500 mg/L or less (depending on availability of SPW). The aqueduct water is characterized by relatively high levels of total dissolved solids, hardness and alkalinity, with moderate levels of organic material and relatively low turbidity.

Figure 3-2 illustrates Lake Skinner water quality for the period of November 1997 through November 1998, which is typical for this source water. The stable quality of the water is apparent in all parameters illustrated in the figure. Hardness ranged from 200 through 298 mg/L as  $\text{CaCO}_3$ , alkalinity ranged from 108 to 130 mg/L as  $\text{CaCO}_3$  and calcium ranged from 47 to 75 mg/L as Ca (118 to 188 mg/L as  $\text{CaCO}_3$ ). The hardness levels are quite high, with relatively high alkalinity as well. TDS ranged from 429 to 610 mg/L, indicating the relatively high level of salinity in this source water. pH ranged from 8.26 to 8.45 during the year.

Figure 3-3 illustrates turbidity, temperature and TOC for Lake Skinner water. Turbidity was relatively low with a range of 1.10 to 3.50 nephelometric turbidity units (NTU). Lake Skinner exhibits relatively warm temperatures throughout the year, typical of many water supplies in the southwestern and southeastern United States. The temperature range was 13 to 27°C. Annual

low temperatures on the order of 10°C are typical of this supply. The levels of organic material, as quantified by TOC, are moderate in this supply. The TOC range was 2.33 to 2.94 mg/L.

### **3.3 Environmental Technology Verification Testing Plan**

This section describes the tasks completed for the ETV. The test equipment was operated 24 hours a day, seven days a week, with operations staff on-site Monday through Friday for one 8-hour shift each day. Tasks that were performed by the operations and engineering staff are listed below:

- Task 1: Characterization of Membrane Flux and Recovery
- Task 2: Evaluation of Cleaning Efficiency
- Task 3: Evaluation of Finished Water Quality
- Task 4: Reporting of Membrane Pore Size
- Task 5: Membrane Integrity Testing
- Task 6: Data Management
- Task 7: Quality Assurance/Quality Control
- Task 8: Microbial Removal (optional)

An overview of each task is provided below.

#### **3.3.1 Task 1: Characterization of Membrane Flux and Recovery**

The objective of this task is to evaluate the membrane operational performance. Membrane productivity was evaluated relative to feedwater quality. The rates of transmembrane pressure increase and/or specific flux decline were used, in part, to evaluate operation of the membrane equipment under the operating conditions being verified and under the raw water quality conditions present during the verification testing period.

##### **Work Plan**

After set-up and shakedown of the membrane equipment, membrane operation was established at the flux condition being verified in this ETV. Testing took place over two 30-day test periods. When substantial specific flux decline occurred before the end of the 30-day test period, chemical cleaning was performed and (if necessary) adjustments to the operational strategy were made. Measurement of the membrane system flows, pressures and temperatures were collected at a minimum of twice a day.

#### **3.3.2 Task 2: Evaluation of Cleaning Efficiency**

An important aspect of membrane operation is the restoration of membrane productivity after specific flux decline has occurred. The objective of this task is to evaluate the effectiveness of chemical cleaning for restoring finished water productivity to the membrane system. The recovery of specific flux and the fraction of original specific flux lost were determined after each chemical cleaning.

## Work Plan

The membrane was operated at the flux condition being verified in this ETV until such time as the termination criteria were reached. The two criteria for cleaning of the membrane were: 1) reaching the minimum specific flux operational limit of the membrane (specific flux < 0.85 gfd/psi), or, 2) completing the 30-day test period. The membrane was chemically cleaned when either of these termination criteria was reached. Chemical cleaning was performed in accordance to the manufacturer procedure (see Appendix A). For the feedwater utilized in this ETV, the manufacturer recommended their typical chemical cleaning procedure using citric acid and caustic cleaning solutions.

The first cleaning step uses a two percent citric acid solution in tap water preheated to 35 °C, with pH in the range 2.0 to 2.5. This is followed by a high pH cleaning step using 0.5 percent caustic solution in tap water preheated to 35 °C, with pH in the range 11 to 12. On the recommendation of Ionics, a proprietary high pH cleaning agent, ROClean L211, manufactured by Avista, was used instead of caustic. This cleaning agent contains the metal chelating agent ethylenediamine tetraacetic acid. The high-pH cleaning step includes a final pH 2 hydrochloric acid rinse to remove potential metal precipitates.

To determine cleaning efficiency, flux-pressure profiles were developed at each stage of the chemical cleaning procedure (i.e., before cleaning, after first chemical solution, after second chemical solution). The slope of the flux-pressure profile represents the specific flux of the membrane at each cleaning stage and was used to calculate the cleaning efficiency indicators. Two primary indicators of cleaning efficiency and restoration of membrane productivity were examined in this ETV:

1. The immediate recovery of membrane productivity, as expressed by the ratio between the final specific flux value of the current filtration run ( $J_{sf}$ ) and the initial specific flux ( $J_{si}$ ) measured for the subsequent filtration run:

$$\text{Recovery of Specific Flux} = 100 \times [1 - (J_{sf} \div J_{si})]$$

where:  $J_{sf}$  = specific flux (gallon/ft<sup>2</sup>/day (gfd)/psi, L/(hr-m<sup>2</sup>)/bar) at end of current run (final)

$J_{si}$  = specific flux (gfd/psi, L/(hr-m<sup>2</sup>)/bar) at beginning of subsequent run (initial)

2. The loss of specific flux capabilities is expressed by the ratio between the initial specific flux for any given filtration run ( $J_{si}$ ) and the specific flux ( $J_{sio}$ ) at time zero, as measured at the initiation of the first filtration run in a series:

$$\text{Loss of Original Specific Flux} = 100 \times [1 - (J_{sf} \div J_{sio})]$$

where:  $J_{sio}$  = specific flux (gfd/psi, L/(hr-m<sup>2</sup>)/bar) at time t = 0 of membrane testing

### **3.3.3 Task 3: Evaluation of Finished Water Quality**

The objective of this task is to evaluate the quality of water produced by the ETV test system. Many of the water quality parameters described in this task were measured on-site. Analyses of the remaining water quality parameters were performed by the City of San Diego Laboratory, a State-certified analytical laboratory.

#### **Work Plan**

The parameters monitored during this ETV and the methods used for their measurement are listed in Table 3-1. Finished water quality was evaluated relative to feedwater quality and operational conditions.

### **3.3.4 Task 4: Reporting of Membrane Pore Size**

Membranes for particle and microbial removal do not have a single pore size, but rather have a distribution of pore sizes. Membrane rejection capabilities are limited by the maximum membrane pore size.

#### **Work Plan**

The manufacturer was asked to supply the 90 percent and the maximum pore size of the membranes being tested in the ETV. The manufacturer was also asked to identify the general method used in determining the pore size values.

### **3.3.5 Task 5: Membrane Integrity Testing**

A critical aspect of any membrane process is the ability to verify that the process is producing a specified water quality on a continual basis. For example, it is important to know whether the membrane is providing a constant barrier to microbial contaminants. The objective of this task is to evaluate one or more integrity monitoring methods for the membrane system.

#### **Work Plan**

The selected methods for monitoring of membrane integrity of the Manufacturer's UF system during this study are described below:

#### **Air Pressure-Hold Test**

The air pressure-hold test is one of the direct methods for evaluation of membrane integrity. This test can be conducted on several membrane modules simultaneously; thus, it can test the integrity of a full rack of membrane modules used for full-scale systems. The test is conducted by pressurizing the filtrate side of the membrane after which the pressure is held and the decay rate is monitored over time. Minimal loss of the held pressure (generally less than 1 psi every 5 minutes) at the filtrate side indicates a passed test, while a significant decrease of the held pressure indicates a failed test.

### **Particle Counting**

On-line particle counting in the size ranges of 2-3 microns (um), 3- 5 um, 5-7 um, 7-10 um, 10-15 um and >15 um was used in this ETV as an indirect method of monitoring membrane integrity.

### **Turbidity Monitoring**

On-line turbidity monitoring was also used in this ETV as an indirect method of monitoring membrane integrity.

### **3.3.6 Task 6: Data Management**

The objective of this task is to establish the protocol for management of all data produced in the ETV and for data transmission between the FTO and the NSF.

#### **Work Plan**

According to EPA/NSF ETV protocols, a data acquisition system was used for automatic entry of on-line testing data into computer databases. Specific parcels of the computer databases for online particle and turbidity were then downloaded for importation into Excel as a comma delimited file. These specific database parcels were identified based on discrete time spans and monitoring parameters. In spreadsheet form, data were manipulated into a convenient framework to allow analysis of membrane equipment operation. For those parameters not recorded by the data acquisition system, field-testing operators recorded data and calculations by hand in laboratory notebooks. Daily measurements were recorded on specially-prepared data log sheets as appropriate.

The database for the project was set up in the form of custom-designed spreadsheets. The spreadsheets were capable of storing and manipulating each monitored water quality and operational parameter from each task, each sampling location, and each sampling time. Data from the log sheets were entered into the appropriate spreadsheet. Following data entry, the spreadsheet was printed out and the printout was checked against the handwritten data sheet. Any corrections were noted on the hard-copies and corrected on the screen, and then a corrected version of the spreadsheet was printed out. Each step of the verification process was initiated by the field testing operator or engineer performing the entry or verification step.

Data from the outside laboratory were received and reviewed by the field testing operator. Data from the on-site lab and City of San Diego Microbiology lab were entered into the data spreadsheets, corrected, and verified in the same manner as the field data. Data from the City of San Diego Water Quality lab were received both electronically and in hardcopy printouts generated from the electronic data.

### **3.3.7 Task 7: Quality Assurance/Quality Control**

An important aspect of verification testing is the protocol developed for quality assurance (QA) and quality control (QC). The objective of this task is to assure the high quality of all measurements of operational and water quality parameters during the ETV.

## **Work Plan**

Equipment flow rates and pressures were documented and recorded on a routine basis. A routine daily walk-through during testing is performed each morning to verify that each piece of equipment or instrumentation is operating properly. On-line monitoring equipment, such as flow meters, are checked to confirm that the read-out matches the actual measurement and that the signal being recorded is correct. Below is a list of the verifications conducted:

## **Monitoring Equipment**

### ***System Pressure Gauges***

Pressure and vacuum gauges supplied with the membrane systems tested were verified against grade 3A certified pressure or vacuum gauges purchased at the start of ETV testing. The certified pressure and vacuum gauges were manufactured by Ashcroft and have an accuracy of 0.25% over their range (0-30 psi pressure). Where possible, system gauges were removed and tested over the expected range of operating pressures against the verification gauge, using a portable hand pump. The Ionics system feed and differential pressure gauges were consistently accurate to within five percent or less over their range. The filtrate pressure gauge was accurate to within 0.2 psi over its range.

### ***System Flow Rates***

Membrane system flow rates were verified volumetrically on a monthly basis near the beginning and end of each test period. System flows were diverted to a 55 gallon graduated tank for approximately two minutes. The measured flow rate was compared with flows indicated on the rotameter and magmeter. Measured and indicated flows agreed to within three percent for the filtrate rotameter. The magmeter consistently measured 1 gpm lower than actual flow. Since the filtrate flow rate was automatically adjusted based on the magmeter reading, this was compensated for during testing by entering a filtrate flow setpoint of 20 gpm into the PLC, resulting in an actual flow rate of 21 gpm.

## **Analytical Methods**

### ***pH***

An Accumet Research Model AR15 laboratory pH meter was used to conduct routine pH readings at the test facility. Daily calibration of the pH meter using pH 4, 7 and 10 buffers was performed. The slope obtained after calibration was recorded. The temperature of the sample when reading sample pH was also recorded.

### ***Temperature***

Accuracy of the feed water inline thermometer was verified against an National Institute for Standards and Technology (NIST)-certified thermometer on 12/12/99 and 4/7/00. Comparisons were made at three temperatures covering the range of anticipated raw water temperatures. In all cases, the raw water thermometer compared to within  $\pm 0.2^{\circ}\text{C}$  of the NIST-certified thermometer.

### ***Turbidity***

On-line turbidimeters were used for measurement of turbidity in the raw and filtrate waters, and a bench-top turbidimeter was used for measurement of the feedwater and backwash waste water.

On-line Turbidimeters: Hach 1720D on-line turbidimeters were used during testing to acquire raw and filtrate turbidities at one-minute intervals. The following procedures were followed to ensure the integrity and accuracy of these data:

- a primary calibration of the on-line turbidimeters (using formazin primary standards) was performed near the beginning of the test periods.
- Aquaview + data acquisition software was used to acquire and store turbidity data. Data were stored to the computer database each minute. After initial primary calibration of the turbidimeters, zero, mid-level and full-strength signals (4, 12 and 20 mA) were output from each turbidimeter to the data acquisition software. The signals received by the data acquisition software from all four on-line turbidimeters had less than one percent error over their range of output (0, 1 and 2 NTU for filtrate, and 0, 10 and 20 NTU for feed) as stored in the Aquaview database.
- the manufacturer's specified acceptable flow range for these turbidimeters is 250 to 750 mL/min. The flow range initially targeted during testing was 500 mL/min +/- 100 mL/min. On-line turbidimeter flows were verified manually with a graduated cylinder and stopwatch daily.
- turbidimeter bodies were drained and sensor optics cleaned approximately every week on an as-needed basis.
- on-line turbidities were compared to desktop turbidities when turbidity samples were collected. Comparative calibrations of the raw water on-line turbidimeter against the Hach 2100N desktop turbidimeter were conducted on an as-needed basis during the course of the testing when the difference between on-line and desktop turbidity readings were greater than approximately 10 percent.
- Approximately 50 part per million (ppm) free chlorine solution was pumped through turbidity sample lines as needed to clean potential buildup from these lines.

Desktop Turbidimeters: A Hach 2100N desktop turbidimeter was used to perform onsite turbidity analyses of raw water, backwash and filtrate samples. Readings were recorded in non-ratio operating mode. The following quality assurance and quality control procedures were followed to ensure the integrity and accuracy of onsite laboratory turbidity data:

Primary calibration of turbidimeter according to manufacturer's specification was conducted on a weekly basis. Secondary standard calibration verification was performed on a daily basis. Three secondary standards (approx. 0.8 NTU, 1.8 NTU and 20 NTU) were recorded after primary calibration and on a daily basis for the remaining 6 days until the next primary calibration. Proficiency samples with a known turbidity of 0.8 NTU were purchased from a commercial supplier. Turbidity proficiency samples were prepared and analyzed every two weeks.

### ***Particle Counting***

Hach 1900 WPC light blocking particle counters were used to monitor particles in raw and filtrate waters. These counters enumerate particles in the range 2 to 800 microns (um).

The particle counters were factory calibrated. Factory calibrations took place on May 25, 1999. The manufacturer recommends factory calibration on a yearly basis. The following procedures were followed to ensure the integrity and accuracy of the on-line particle data collected:

- The Aquaview software was configured to store particle counts in the following size ranges: 2-3 um, 3-5 um, 5-7 um, 7-10 um, 10-15 um and >15 um.
- To demonstrate the comparative response of the particle counters, NIST traceable monospheres were purchased from Duke Scientific in the following sizes: 2 um, 4 um, 10 um and 20 um. Duke monospheres were added to constantly stirred deionized (DI) water and pumped to one of the constant head flow controllers using a peristaltic pump. The flow from this controller was then directed to each of the particle counters for approximately 10 minutes. The same solution was used for each particle counter (raw water and filtrate).

The precise concentration of each monosphere was not known, but based on Duke Scientific estimates the following approximate concentration of each monosphere was present in the test solution:

• 2 um	1,000 - 10,000/mL
• 4 um	100 - 1,000/mL
• 10 um	10 - 100/mL
• 20 um	1 - 10/mL

A typical response of the particle counters to this monosphere solution near both test periods is presented in Figure 3-4. The figures show a good comparative response of the raw water and filtrate particle counters to the same monosphere solution.

Flows through the particle counters were maintained at 200+/- 10 mL/min with constant head devices. Flows were verified on a daily basis with a graduated cylinder and stop watch. Flows were observed to be extremely consistent (typically within 2 mL/min of the target flow rate). Fifty mg/L free chlorine was run through particle counters for on an as-needed basis to remove potential buildup.

### **Chemical and Microbial Water Quality Parameters**

The analytical work for the study was performed by the City of San Diego Laboratory, which is a State of California certified water laboratory. All water samples were collected in appropriate containers (containing preservatives as applicable) prepared by the City of San Diego laboratory. Samples for analysis of Total Coliforms (TC) and Heterotrophic Plate Count (HPC) analysis were collected in bottles supplied by the City of San Diego laboratory and transported with an internal cooler temperature of approximately 2 to 8°C to the analytical laboratory. All samples were preserved, stored, shipped and analyzed in accordance with appropriate procedures and holding times. All reported results had acceptable QA and met method-specific QC guidelines, which was confirmed by letters from the City of San Diego Water Quality and Marine Microbiology

Laboratories (Appendix A). For the Marine Microbiology Laboratory, these QC procedures included the use of positive / negative controls, blanks and sterility checks.

### **3.3.8 Task 8: Microbial Removal (Optional)**

The objective of this task is to evaluate microbial removal capabilities by seeding the membrane system with selected virus. Removal capabilities were evaluated under the worst case scenario for the membrane system operation (in this case, directly after chemical cleaning of the membranes).

#### **Work Plan**

The seeding experiments were performed at the test site and the samples collected during the seeding experiments were submitted to the City of San Diego Marine Microbiology Lab, a State-certified laboratory, for analysis of the seeded microorganisms.

#### **Organisms for Seeding Experiments**

The organism selected for seeding experiments is MS2 bacterial virus. MS2 virus is not a human pathogen; however, this organism is similar in size (0.025 microns), shape (icosahedron) and nucleic acid (RNA) to polio and hepatitis virus. Since MS2 is not a human pathogen, live MS2 virus was used in the seeding experiments. Organism stocks received from the suppliers were stored refrigerated at 4°C in the dark until use in the seeding experiments.

#### **Microbial Seeding Protocols**

The virus were added to approximately 100 gallons (380 liter) of dechlorinated tap water in a 55 gallon polyethylene tank. A peristaltic pump was used to continuously add this virus stock solution to the membrane feed water. During the MS2 seeding experiment, three samples from the membrane feed water and three samples from the filtrate water were collected during the second and third service cycles after the initiation of seeding. The first filtrate sample during each filtration cycle was collected within the first minute of filtration after completion of backwash. The last filtrate sample during each filtration cycle was collected within 3 minutes of the end of the cycle. Each sample was collected in sterile 250-mL bottles, was stored at 1°C and processed within 24 hours. The microorganism concentration in the feed water was sufficient to demonstrate a minimum of 4 logs of removal of the seeded organism.

The MS2 seeding experiments were conducted at the end of Test Period 1 and the beginning of Test Period 2. The experiments were conducted under the operating conditions in which the microorganisms would most likely penetrate the membrane; when the membrane is clean, and at a high flux rate (Jacangelo et al. 1995, Montgomery Watson, 1997). Therefore, the membrane was cleaned immediately prior to MS2 seeding.

### 3.4 Calculation of Membrane Operating Parameters

#### 3.4.1 Filtrate Flux

The average filtrate flux is the flow of filtrate water divided by the surface area of the membrane. Filtrate flux is calculated according to the following formula:

$$J_t = Q_p \div S$$

where  $J_t$  = filtrate flux at time t (gfd, L/(hr-m<sup>2</sup>))  
 $Q_p$  = filtrate flow (gallon per day (gpd), L/hr)  
 $S$  = membrane surface area (ft<sup>2</sup>, m<sup>2</sup>)

Flux is expressed only as gfd and L/(hr-m<sup>2</sup>) in accordance with EPA/NSF ETV protocol.

#### 3.4.2 Specific Flux

The term specific flux is used to refer to filtrate flux that has been normalized for the transmembrane pressure. The equation used for calculation of specific flux is:

$$J_{tm} = J_t \div P_{tm}$$

where  $J_{tm}$  = specific flux at time t  
(gfd/psi, L/(hr-m<sup>2</sup>)/bar)  
 $J_t$  = filtrate flux at time t (gfd, L/(hr-m<sup>2</sup>))  
 $P_{tm}$  = transmembrane pressure (psi, bar)

#### 3.4.3 Transmembrane Pressure

The average transmembrane pressure is calculated as follows:

$$P_{tm} = [(P_i + P_o) \div 2] - P_p$$

where  $P_{tm}$  = transmembrane pressure (psi, bar)  
 $P_i$  = pressure at the inlet of the membrane module (psi, bar)  
 $P_o$  = pressure at the outlet of the membrane module (psi, bar)  
 $P_p$  = filtrate pressure (psi, bar)

#### 3.4.4 Temperature Adjustment for Flux Calculation

Temperature corrections to 20°C for transmembrane flux were made to account for the variation of water viscosity with temperature. The following equation was employed:

where  $J_t$  = instantaneous flux (gfd, L/(hr-m<sup>2</sup>))  
 $Q_p$  = filtrate flow (gpd, L/hr)  
 $T$  = temperature, (°F, °C)  
 $S$  = membrane surface area (ft<sup>2</sup>, m<sup>2</sup>)

### 3.4.5 Feedwater System Recovery

The recovery of filtrate from feedwater is the ratio of filtrate flow to feedwater flow:

$$\% \text{ System Recovery} = 100 \times (Q_p/Q_f)$$

where  $Q_p$  = filtrate flow (gpd, L/hr)  
 $Q_f$  = feed flow to the membrane (gpd, L/hr)

### 3.4.6 Rejection

The rejection of contaminants by membrane process was calculated as follows:

$$R = (1 - \frac{C_p}{C_F}) * 100\%$$

where:  $R$  = Rejection, %  
 $C_p$  = Filtrate water concentration, (mg/L)  
 $C_F$  = Feed water concentration, (mg/L)

## 3.5 Calculation of Data Quality Indicators

### 3.5.1 Precision

As specified in Standard Methods (Method 1030 C), precision is specified by the standard deviation of the results of replicate analyses. An example of replicate analyses in this ETV is the biweekly analysis of turbidity proficiency samples. The overall precision of a study includes the random errors involved in sampling as well as the errors in sample preparation and analysis.

$$\text{Precision} = \text{Standard Deviation} = \sqrt{\sum_{i=1}^n (\bar{X}_i - \bar{X})^2 \div (n - 1)}$$

where:  $\bar{X}$  = sample mean  
 $\bar{X}_i$  =  $i$ th data point in the data set  
 $n$  = number of data points in the data set

### 3.5.2 *Relative Percent Deviation*

For this ETV, duplicate samples were analyzed to determine the overall precision of an analysis using relative percent deviation. An example of duplicate sampling in this ETV is the daily duplicate analysis of turbidity samples using the bench-top turbidimeter.

$$\text{Relative Percent Deviation} = 100 \times [(x_1 - x_2) \div \bar{X}]$$

where  $\bar{X}$  = sample mean  
 $x_1$  = first data point of the set of two duplicate data points  
 $x_2$  = second data point of the set of two duplicate data points

### 3.5.3 *Accuracy*

Accuracy is quantified as the percent recovery of a parameter in a sample to which a known quantity of that parameter was added. An example of an accuracy determination in this ETV is the analysis of a turbidity proficiency sample and comparison of the measured turbidity to the known level of turbidity in the sample.

$$\text{Accuracy} = \text{Percent Recovery} = 100 \times [X_{\text{measured}} \div X_{\text{known}}]$$

where  $X_{\text{known}}$  = known concentration of measured parameter  
 $X_{\text{measured}}$  = measured concentration of parameter

### 3.5.4 *Statistical Uncertainty*

For the water quality parameters monitored, 95 percent confidence intervals were calculated. The following equation was used for confidence interval calculation:

$$\text{Confidence Interval} = \bar{X} \pm [t_{n-1, 1 - (\alpha/2)} \times (S/\sqrt{n})]$$

where:  $\bar{X}$  = sample mean  
 $S$  = sample standard deviation  
 $n$  = number of independent measurements included in the data set  
 $t$  = Student's t distribution value with n-1 degrees of freedom  
 $\alpha$  = significance level, defined for 95 percent confidence as:  $1 - 0.95 = 0.05$

According to the 95 percent confidence interval approach, the  $\alpha$  term is defined to have the value of 0.05, thus simplifying the equation for the 95 percent confidence interval in the following manner:

$$95 \text{ Percent Confidence Interval} = \bar{X} \pm [t_{n-1,0.975} \times (S/\sqrt{n})]$$

### **3.6 Testing Schedule**

The ETV schedule is illustrated in Figure 3-5. The testing project took place starting in December 1999 and finishing by the beginning of April 2000. Test Period 1 represented the winter season and Test Period 2 represented the spring season.

## Chapter 4

### Results and Discussion

This chapter presents the data obtained under each task of the ETV project of the Ionics UF system.

#### 4.1 Task 1: Characterization of Membrane Flux and Recovery

The operating conditions for the Ionics UF membrane system are provided in Table 4-1. The manufacturer established the operating parameters for the ETV testing. The membrane system ran at a target flux of 33 gfd ( $57 \text{ L/hr-m}^2$ ). Filtration cycle length was 30 minutes followed by a 60 to 65 second “B” backwash or 130 to 155 second “C” backwash. Nine “B” backwashes were performed before a “C” backwash was performed and the pressure vessel was drained. Filtrate consumed during backwash was 15 gallons (57 liters) for Test Period 1 and 30 gallons (113 liters) for Test Period 2. Feed water consumed during backwash was 30 gallons (113 liters) during Test Period 1 and 7 gallons (26 liters) during Test Period 2. The backwash feed water was chlorinated at 5 - 10 mg/L during reverse flow. The feed water recovery was 93 percent during Test Period 1 and 92 percent during Test Period 2.

Figure 4-1 (A and B) provides the membrane transmembrane pressure and temperature profiles for Test Periods 1 and 2. Operational readings were taken approximately 5 minutes before and after backwash. These are displayed on the figures as pairs of data points at nearly the same point in time. The data point taken before backwash has the higher transmembrane pressure value. For Test Period 1, the clean membrane transmembrane pressure began at approximately 6 psi. The transmembrane pressure stabilized at 7 to 10 psi for approximately 2.5 weeks and then fouled more rapidly over the remainder of the filter run. Transmembrane pressure at the beginning of Test Period 2 was 6 psi. The transmembrane pressure remained between 7 and 10 psi for the remainder of Test Period 2. The changes made to the backwash conditions between Test Periods 1 and 2 are likely responsible for the improved fouling performance during Test Period 2.

Figure 4-2 (A and B) provides the membrane flux and specific flux profiles for Test Periods 1 and 2. The target flux during Test Periods 1 and 2 was 33 gfd ( $57 \text{ L/hr-m}^2$ ). For Test Period 1, the average temperature adjusted membrane flux was 37 gfd at  $20^\circ\text{C}$  ( $63 \text{ L/hr-m}^2$  at  $20^\circ\text{C}$ ). Due to the relatively higher water temperatures during Test Period 2, a lower average temperature adjusted membrane flux of 34 gfd at  $20^\circ\text{C}$  ( $58 \text{ L/hr-m}^2$  at  $20^\circ\text{C}$ ) was observed. The temperature adjusted specific flux decreased from 6 to 1 gfd/psi at  $20^\circ\text{C}$  ( $148$  to  $25 \text{ L/hr-m}^2\text{-bar}$  at  $20^\circ\text{C}$ ) over the 35 days of Test Period 1. Temperature adjusted specific flux decreased from 5.8 to 4.8 gfd/psi at  $20^\circ\text{C}$  ( $143$  to  $118 \text{ L/hr-m}^2\text{-bar}$  at  $20^\circ\text{C}$ ) over the first 3 days of operation in Test Period 2. Temperature corrected specific flux then gradually decreased to 3.8 gfd/psi at  $20^\circ\text{C}$  ( $94 \text{ L/hr-m}^2\text{-bar}$  at  $20^\circ\text{C}$ ) by the end of Test Period 2.

The same data in Figures 4-1 and 4-2 are also provided in Appendix A of this report, but with metric units.

## **4.2 Task 2: Evaluation of Cleaning Efficiency**

Chemical cleanings were performed when the membrane fouled (transmembrane pressure in the range 15 to 20 psi [1.0 to 1.4 bar]), or the end of a test period was reached. The manufacturer's cleaning procedure was a two step process. A citric acid cleaning solution was used first, followed by a high pH cleaning solution. The 2 percent citric acid cleaning solution was prepared by dissolving 17 pounds (37 kg) of citric acid in approximately 30 gallons of tap water preheated to 35 °C. The pH of this solution was in the range 2 to 2.5. The citric acid solution was placed in the feed tank and recirculated through the feed side of the membrane for 60 minutes at a flow of 330 gpm (125 L/min) with a feed pressure of approximately 15 psi. After this, filtrate flow was adjusted to 21 gpm (79 L/min) and the cleaning solution was allowed to recirculate for an additional 15 minutes. After discarding the cleaning solution and rinsing the system with tap water, the same cleaning procedure was followed using a high pH cleaning solution. The high pH cleaning solution was made by adding 1.8 gallon (7 liters) of Avista ROClean L211 to 100 gallons tap water preheated to 35 °C. The pH of this solution was in the range 10.5. Since the high pH cleaning solution was prepared in tap water, the caustic cleaning step included a pH 2 hydrochloric acid rinse to remove any precipitates that potentially formed under these conditions.

The flux-pressure profiles of the membrane system at different stages of the chemical cleaning procedure for Test Periods 1 and 2 are shown in Figures 4-3 and 4-4, respectively. The slope of the flux-pressure profile represents the specific flux of the membrane at each cleaning stage and was used to calculate the cleaning efficiency indicators. These are listed in Table 4-2. The recovery of specific flux for the cleanings at the end of Test Period 1 and 2 were 78 percent and 23 percent, respectively. The lower recovery after the cleaning at the end of Test Period 2 was due to the fact the membrane was not completely fouled when the cleaning was conducted and because the specific flux after cleaning was not as high as during the previous cleaning.

The membrane lost 4.8 percent of original specific flux after cleaning at the end of Test Period 1. The loss of original specific flux increased to 17 percent after the cleaning at the end of Test Period 2. Because of the limited number of cleanings, the usable membrane life can not be estimated.

The same data in Figures 4-3 and 4-4 are also provided in Appendix A of this report, but with metric units. In addition, the manufacturer's detailed cleaning procedure is included in Appendix A.

## **4.3 Task 3: Evaluation of Finished Water Quality**

Several water quality parameters were monitored during testing. Below is a summary of the water quality data.

### ***4.3.1 Turbidity, Particle Concentration and Particle Removal***

Figures 4-5 and 4-6 present the on-line turbidity profile for the Ionics UF membrane system during Test Periods 1 and 2, respectively. The figures show online turbidity for raw and filtrate water and desktop turbidity for raw water, filtrate and backwash waste. The desktop turbidity data are summarized in Table 4-3 and the online turbidity data are summarized in Table 4-4. For both testing periods, the raw water turbidity was in the range of 1-3 NTU. The turbidity of the backwash waste water averaged about 17 NTU for Test Period 1 and 12 NTU for Test Period 2. The filtrate turbidity was typically below 0.1 NTU.

Figures 4-7 and 4-8 present the particle count profile (2-3  $\mu\text{m}$ , 3-5  $\mu\text{m}$ , 5-7  $\mu\text{m}$ , 7-10  $\mu\text{m}$ , 10-15  $\mu\text{m}$  and  $>15 \mu\text{m}$ ) collected during Test Periods 1 and 2, respectively. The data presented represent 4-hour average values of data collected at one-minute intervals. For both testing periods, the feed particle concentration of the *Cryptosporidium*-sized particles (3-5  $\mu\text{m}$ ) were in the range of 1,000 to 10,000 particle/mL while the combined *Giardia*-sized particles (5-7  $\mu\text{m}$ , 7-10  $\mu\text{m}$  and 10-15  $\mu\text{m}$ ) were in the range 300 to 1,500 particle/mL. The filtrate concentration in these size ranges was typically in the range of 0.04 to 3 particle/mL during Test Period 1. The gap in the particle data near December 25, 1999 was due to an electrical power failure to the particle counters. The gap at January 1, 2000 was due to a Y2K related software failure. The sudden increase in filtrate particle concentration on January 3, 2000 was due to a single broken fiber. After removing the pressure vessel cover, a bubble-point test was conducted and one compromised fiber was detected and repaired. Since both ends of the fiber are potted, two air bubbles would be expected from both ends. However, the fibers tended to break near the potting material and the fiber end with the long fiber attached frequently did not produce visible bubbles.

Filtrate particle levels during Test Period 2 exhibit a general increasing trend. During the course of Test Period 2, a number of incidents of broken fibers were detected by visual observation of real time filtrate particle counts. The repairs near the beginning of Test Period 2 were generally successful in decreasing particle counts to near pre-break levels. Two compromised fibers were detected, via the bubble point test, after the break that occurred on March 13, 2000 and were repaired on March 15, 2000. One compromised fiber was detected from the break that occurred on March 20, 2000 and was repaired on March 22, 2000. One compromised fiber was detected from a break that occurred on March 26, 2000 and was repaired on March 28, 2000. It was observed during the repair of March 28, 2000 that the potting material around the leaking fiber end was damaged and that the stainless steel pin used to make the repair was not seating tightly. During a repair of the same leaking fiber end on March 31, 2000, a larger pin was installed, but filtrate particle counts never recovered to previous levels. It was believed that this repaired fiber end continued to leak, to lesser degrees, for the remainder of Test Period 2. Particle removals were lower during periods of operation with compromised fibers.

Figures 4-9 and 4-10 present the log removal of particles (2-3  $\mu\text{m}$ , 3-5  $\mu\text{m}$ , 5-7  $\mu\text{m}$ , 7-10  $\mu\text{m}$ , 10-15  $\mu\text{m}$ , and  $>15 \mu\text{m}$ ) based on raw and filtrate particle count data collected during Test Periods 1 and 2, respectively. Data presented on this plot represent one-day average values of data collected at one minute intervals. Removal ranged from 3.0 to 4.6 logs for the *Cryptosporidium*-sized particles (3-5  $\mu\text{m}$ ) and from 2.8 to 4.2 logs for the *Giardia*-sized particles (5-7  $\mu\text{m}$ , 7-10  $\mu\text{m}$  and 10-15  $\mu\text{m}$ ) during Test Period 1. Removals decreased to between 2.9 to 3.9 logs for the

*Cryptosporidium*-sized particles and to between 2.6 to 3.9 logs for the *Giardia*-sized particles during Test Period 2. The online turbidity and particle removal data are summarized in Table 4-4.

To assist in assessing test system performance, Figure 4-11 presents the probability plots of the membrane system filtrate turbidity and particle removal data for the *Cryptosporidium*-sized particles (3-5  $\mu\text{m}$ ) and *Giardia*-sized particles (5-15  $\mu\text{m}$ ). The figure shows that the filtrate turbidity was 0.05 NTU or below 95 percent of times and that removal of particles (3-5  $\mu\text{m}$  and 5-15  $\mu\text{m}$ ) was greater than 3 logs 95 percent of times.

#### **4.3.2 Indigenous Bacteria Removal**

The removal of naturally occurring bacteria was also monitored during the ETV study (see Table 4-5). The raw water total coliform bacteria ranged from <2 to 80 most probable number (MPN)/100mL during Test Period 1 and from <2 to 17 MPN/100mL during Test Period 2. Total coliforms bacteria were not detected in the filtrate of the Ionics UF membrane system during either test period. HPC bacteria were not reduced by membrane filtration. This could be due to the fact some fibers were compromised and repaired during the testing, which may have contaminated the filtrate side. Previous studies (Jacangelo et al., 1995) have demonstrated that HPC bacteria can be introduced on the filtrate side of the membrane rather than by penetration through it. HPC bacteria in the raw water ranged from 2 to 120 colony forming units (cfu)/mL during Test Period 1 and from 2 to 1400 cfu/mL in Test Period 2. HPC bacteria in the Ionics UF filtrate ranged from 11 to 140 cfu/mL during Test Period 1 and from 48 to 580 cfu/mL during Test Period 2.

#### **4.3.3 Other Water Quality Parameters**

Table 4-6 presents the results of general water quality parameters across the Ionics UF system for Test Periods 1 and 2. As expected, no change was observed in the alkalinity, total dissolved solids, total hardness, and calcium hardness of the water across the membrane system. No reduction in organic material in the filtrate was observed.

The total suspended solids (TSS) in the backwash waste reached as high as 68 mg/L (during Test Period 1), while the filtrate TSS remained consistently below the detection limit (1 mg/L).

Table 4-7 presents the mass balance conducted on total suspended solids across the membrane system. Only the result of December 8, 1999 falls within the calculated range of TSS assuming either the first or ninth “B” backwash following a “C”. The relatively poor predictions of actual backwash TSS may in part be due to the TSS in the raw water being near the detection limit of the analysis, 1 mg/L.

#### **4.4 Task 4: Reporting Membrane Pore Size**

A request was submitted to the membrane Manufacturer to provide the 90 percent and maximum pore size of the membrane being verified. In their response letter, Ionics stated the 90 percent pore size is 0.01  $\mu\text{m}$  as determined by Field Emission Scanning Electron Microscope. The letter further stated the 100 percent pore size was 0.04  $\mu\text{m}$  as determined by latex.

The above information are taken from a letter supplied by the Ionics which is included in Appendix A of this report. This is provided for informational purposes only and the results were not verified during the ETV testing.

#### **4.5 Task 5: Membrane Integrity Testing**

Figure 4-12 shows the results of the air pressure-hold tests conducted on the UF membrane during Test Periods 1 and 2. The air pressure-hold test on the Ionics system was conducted by pressurizing the feed side of the membrane. If any of the membrane fibers were compromised, one would expect significant loss of held pressure ( $> 1$  psi every 5 minutes) across the membrane element. The air pressure-hold tests conducted before and after repairs of broken fibers did not consistently support this test criteria. During the air pressure-hold test before the first repair conducted on January 4, 2000, the pressure decay was only 0.6 psi over 10 minutes. While two bubble points were observed, on March 15, 2000, the air pressure-hold tests before and after repair showed identical pressure decays of 1.6 psi.

During other fiber breakage incidents, pressure decay slightly over 2 psi over 10 minutes was observed in the system with compromised fibers. In the air pressure-hold tests conducted before repairs on March 22, 28 and 31 the pressure decay was slightly greater than 2 psi in 10 minutes.

While there were a number of fiber breakage incidents over the course of testing, the turbidity profiles shown in Figures 4-5 and 4-6 show consistently low filtrate turbidity levels. Thus, turbidity monitoring was not useful in detecting 2 or less compromised fibers.

Filtrate particle counts would be expected to noticeably increase if the membrane modules were compromised (Adham et. al., 1995, Montgomery Watson, 2000). During testing of the Ionics UF system, particle counting was a reliable method of determining membrane integrity. Every fiber breakage was displayed in real time on the computer display. Air pressure-hold tests were conducted after this to verify loss of membrane integrity. The air pressure-hold test was followed by bubble-point testing to identify leaking fibers.

#### **4.6 Task 6: Data Management**

##### **4.6.1 Data Recording**

Data were recorded manually on operational and water quality data sheets prepared specifically for the study. In addition, other data and observations such as the system calibration results were recorded manually on laboratory and QC notebooks. Data from the particle counters and

turbidimeters were also recorded via data acquisition system. All of the raw data sheets are included in Appendix B of this report.

#### ***4.6.2 Data Entry, Validation, and Reduction***

Data were first entered from raw data sheets into similarly designed data entry forms in a spreadsheet. Following data entry, the spreadsheet was printed and checked against handwritten datasheets. All corrections were noted on the electronic hard copies and then corrected on the screen. The hardcopy of the electronic data are included in Appendix C of this report.

### **4.7 Task 7: Quality Assurance/Quality Control (QA/QC)**

The objective of this task is to assure the high quality and integrity of all measurements of operational and water quality parameters during the ETV project. Below is a summary of the analyses conducted to ensure the correctness of the data.

#### ***4.7.1 Data Correctness***

Data correctness refers to data quality, for which there are five indicators:

- Representativeness
- Statistical Uncertainty
- Completeness
- Accuracy
- Precision

Calculation of the above data quality indicators were outlined in the Materials and Methods section. All water quality samples were collected according to the sampling procedures specified by the EPA/NSF ETV protocols, which ensured the representativeness of the samples. Below is a summary of the calculated indicators.

#### ***4.7.2 Statistical Uncertainty***

Ninety-five percent confidence intervals were calculated for the water quality parameters of the Ionics UF system. These include turbidity, particle count, particle removal, and indigenous bacteria. Ninety-five percent confidence intervals were presented in summary tables in the discussion of Task 3 – Finished Water Quality.

#### ***4.7.3 Completeness***

Data completeness refers to the amount of data collected during the ETV study as compared to the amount of data that were proposed in the FOD. Calculation of data completeness was made for onsite water quality measurements, laboratory water quality measurements, and operational data recording. These calculations are presented in Appendix A of this report. Nearly all parameters were 100 percent complete. Overall, the database of laboratory water quality data and

operational readings was more than 85 percent complete, which met the objective of the ETV project.

#### **4.7.4 Accuracy**

Accuracy is quantified as the percent recovery of a parameter in a sample to which a known quantity of that parameter was added. An example of an accuracy determination in this ETV is the analysis of a turbidity proficiency sample and comparison of the measured turbidity to the known level of turbidity in the sample. Calculation of data accuracy were made to ensure the accuracy of the onsite desktop turbidimeter used in the study. Accuracy ranged from 102 to 105 percent of the proficiency sample known values. Comparative calibration of online turbidimeters with the desktop turbidimeters were performed as corrective actions as needed. All accuracy calculations are presented in Appendix A.

#### **4.7.5 Precision and Relative Percent Deviation**

Duplicate water quality samples were analyzed to determine the consistency of sampling and analysis using relative percent deviation. Calculations of relative percent deviation for duplicate samples are included in Appendix A of this report. The relative percent deviation for analyses not near the lower detection limit were within 15 percent for onsite analyses, within 41 percent for other general water quality analyses, and within 75 percent for microbial analyses. Relative percent deviation for online and desktop turbidimeter results were also conducted.

### **4.8 Task 8: Microbial Removal**

To demonstrate microbial removal by the Ionics UF system, two seeding experiments with MS2 bacterial virus were conducted. The two seeding experiments were conducted during each test period, immediately after a membrane cleaning. The clean membrane condition provides worst case conditions for virus removal (Jacangelo et al. 1995, Montgomery Watson, 1997).

The feed and filtrate concentrations and log removal of virus during this seeding are presented in Table 4-8 and Figure 4-13. The membrane virus rejection ranged from 4.0 to 5.7 logs for the seeding conducted at the end of Test Period 1 and from 2.9 to 4.3 logs for the seeding conducted at the beginning of Test Period 2.

### **4.9 Additional ETV Project Requirements**

#### **4.9.1 Operation and Maintenance (O&M) Manual**

The O&M manual for the Ionics UF system supplied by the manufacturer was reviewed during the ETV testing project. The review comments for the O&M manual are presented in Table 4-9. The review found the O&M manual to be an extremely useful resource. The manual is very well organized, well written, clear and complete. The manual makes excellent use of tables and graphics to organize and clarify the presentation of material. The manual includes a complete set of manufacturer information sheets for components used on the membrane system.

#### ***4.9.2 System Efficiency and Chemical Consumption***

The efficiency of the small-scale Ionics UF system was calculated based on the electrical usage and water production of the system. The data are presented in Table 4-10. Overall, an efficiency of only 20 percent was calculated for the system. This system, however, is significantly more efficient than many small-scale low pressure membrane systems.

The chemical consumption of the system was also estimated based on the operating criteria used during the ETV project. Table 4-11 provides a summary of the chemical consumption of the small-scale Ionics UF system.

#### ***4.9.3 Equipment Deficiencies Experienced During the ETV Project***

##### **Test Period 1**

##### ***Ionics UF Membrane System***

At the beginning of Test Period 1, frequent problems of inconsistent output from the positive displacement pump used to chlorinate the backwash feed water were encountered. On December 10, 1999 a pump from a different manufacturer was installed. After this the chlorine feed to the backwash water was consistent.

On January 3, 2000 at 11:30, the minimum filtrate > 2 um particle counts increased from 0.04/mL to approximately 2/mL. On January 5, 2000 the top of the pressure vessel was removed and upon pressurization, 1 bubble point was identified. This leaking fiber end was repaired with a stainless pin. Filtrate particle counts returned to previous low levels by January 6, 2000.

##### ***Online Turbidimeters and Particle Counters***

The raw water online turbidimeter failed on December 8, 1999. A spare turbidimeter was used to record raw water turbidity while this unit was returned to the manufacturer for repair.

On January 1, 2000 the online turbidity and particle count data acquisition software crashed. Since this occurred over a holiday weekend, it caused an approximately 3 day period where no online particle and turbidity data were collected.

##### **Test Period 2**

##### ***Ionics UF Membrane System***

The membrane system experienced 3 incidents of broken fibers over the course of Test Period 2. In all cases, the fiber breakage was identified by visual observation of online filtrate particle count data.

In the first incident on March 13, 2000, 2 bubble points were identified and repaired. In the second fiber breakage incident on March 20, 2000, one bubble point was identified and repaired. After the final incident on March 26, 2000, which identified one bubble point, repairs were not successful in restoring particle counts to previous levels because of damage to the potting material around the broken fiber end. A second attempt at repairing this fiber end on March 31, 2000 was also unsuccessful. Repairs were easily accomplished by inserting stainless steel pins into the

leaking fiber ends at the top of the module. The most time-consuming aspect of the repair procedure was removing the approximately two dozen bolts connecting the pressure vessel cover to the base of the pressure vessel.

A chronological listing of all problems experienced during ETV testing of the Ionics UF system, along with their associated corrective actions, is provided in Appendix A of this report.

## Chapter 5

### References

- Adham, S.S., J.G. Jacangelo, and J-M. Laîné (1995). Low pressure membranes: assessing integrity, *Journal AWWA*, 87(3)62-75.
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- Jacangelo, J.G., S.S. Adham, and J-M. Laîné (1995). Mechanism of *Cryptosporidium*, *Giardia*, and MS2 virus removal by MF and UF, *Journal AWWA*, 87(9)107-121.
- Montgomery Watson (1997), *Membrane Prequalification Pilot Study*. Final Report prepared for the City of San Diego, October 1997.
- Sobsey, M.D., Schwab, K.J., and Handzel, T.R. (1982) A simple membrane filter method to concentrate and enumerate male-specific RNA coliphages. *Jour AWWA*, (9):52-59.

## **Tables and Figures**

**Table 2-1. Characteristics of the Ionics UF 1-7T ultrafiltration membrane.**

	<b>Units</b>	<b>Value</b>
Membrane Manufacturer		TORAY
Membrane Model		TP-TE07-S
Commercial Designation		IONICS UF 1-7T
Available Operating Modes		dead-end
Approximate Size of Membrane Module	ft (m)	3.3 (1.0) length x 0.29 (0.089) diam
Active Membrane Area	ft <sup>2</sup> (m <sup>2</sup> )	130 (12)
Number of Fibers per Module		3,600 (approx.)
Number of Modules (Operational)		7
Inside Diameter of Fiber	inch (mm)	0.016 (0.40)
Outside Diameter of Fiber	inch (mm)	0.027 (0.68)
Approximate Length of Fiber	ft (m)	5.2 (1.6)
Flow Direction		outside-in
Nominal Membrane Pore Size	micron	0.01
Absolute Membrane Pore Size	micron	0.04
Membrane Material/Construction		PolyAcryloNitrile
Membrane Surface Characteristics		Hydrophilic
Membrane Charge		Neutral
Design Operating Pressure	psi (bar)	7.3 (0.50)
Design Flux at Design Pressure	gfd (l/hr-m <sup>2</sup> )	69 (117)
Maximum Transmembrane Pressure	psi (bar)	44 (3.0)
Standard Testing pH		7
Standard Testing Temperature	degF (degC)	77 (25)
Acceptable Range of Operating pH Values		2-10 (operating), 1-12 (cleaning)
Maximum Permissible Turbidity	NTU	300 (experience up to)
Chlorine/Oxidant Tolerance		Chlorine tolerant

**Table 3-1. Water quality analytical methods.**

Parameter	Facility	Standard Method
<b>General Water Quality</b>		
pH	On-Site	4500H+
Alkalinity	Laboratory	2320 B
Total Hardness	Laboratory	2340 C
Calcium Hardness	Laboratory	3500Ca D
Temperature	On-Site	2550 B
Total Suspended Solids	Laboratory	2540 D
Total Dissolved Solids	Laboratory	2540 C
<b>Particle Characterization</b>		
Turbidity (Bench-Top)	On-Site	2130 B
Turbidity (On-Line)	On-Site	Manufacturer
Particle Counts (On-Line)	On-Site	Manufacturer
<b>Organic Material Characterization</b>		
TOC and DOC	Laboratory	5310 B
UV Absorbance at 254 nm	Laboratory	5910 B
<b>Microbiological Analyses</b>		
Total Coliform	Laboratory	9221 B
HPC Bacteria	Laboratory	9215 B
MS2 Virus	Laboratory	EPA ICR Method for Coliphage Assay

**Table 4-1. Ionics UF membrane system operating conditions.**

Parameter	Unit		
Test Period		1	2
Run		1-1	2-1
Start Date & Time		12/7/99 17:00	3/6/00 15:16
End Date & Time		1/11/00 10:32	4/6/00 14:23
Run Length	days - hrs	34 days - 18 hrs	30 days - 23 hrs
Run Terminating Condition		Time	Time
Filter Cycle Length	min	30	30
Feed Flow	gpm (lpm)	21 (79)	21 (79)
Filtrate Flow	gpm (lpm)	21 (79)	21 (79)
Operating Flux	gfd (L/hr-m <sup>2</sup> )	33 (57)	33 (57)
<b>"B" Backwash Settings</b>			
Backwash Cycle Length	sec	60	65
Backwash Filtrate Consumed	gal (liter)	15 (57)	30 (113)
Fast Flush Feedwater Consumed	gal (liter)	30 (114)	7 (26)
Number of "B" backwash before a "C"		9	9
<b>"C" Backwash Settings</b>			
Backwash Cycle Length	sec	130	155
Backwash Filtrate Consumed	gal (liter)	10 (38)	30 (113)
Fast Flush Feedwater Consumed	gal (liter)	45 (170)	45 (170)
Backwash Chlorine Dose (during reverse flow)	mg/L	5 - 10	5 - 10
Feed Water Recovery	%	93%	92%

**Table 4-2. Evaluation of cleaning efficiency for Ionics UF membrane.**

Clean Number	Clean Date	Specific Flux @20degC Before Clean Jsf gfd/psi (l/hr-m2-bar)	Specific Flux @20degC After Clean Jsi gfd/psi (l/hr-m2-bar)	Recovery of Specific Flux 100(1 - Jsf / Jsi) %	Loss of Original Specific Flux 100(1-(Jsi / Jsio)) %
Start		---	5.1 (126)	---	---
1-1	1/11/00	1.1 (27)	4.8 (120)	78	4.8
2-1	4/7/00	3.2 (80)	4.2 (104)	23	17

**Table 4-3. Onsite lab water quality analyses for Ionics UF membrane system.**

Parameter	Unit	Count	Median	Range	Average	Standard Deviation	95 Percent Confidence Interval
<b>TEST PERIOD 1</b>							
<b>Raw Water</b>							
pH		23	8.3	8.1 - 8.5	8.3	0.071	8.3 - 8.3
Desktop Turbidity	NTU	46	1.2	1.0 - 1.5	1.2	0.12	1.2 - 1.2
Temperature	degC	46	17	7.0 - 21	15	3.5	14 - 16
<b>Filtrate</b>							
Desktop Turbidity	NTU	22	0.05	0.05 - 0.05	0.05	0.00	0.05 - 0.05
<b>Backwash Waste</b>							
Desktop Turbidity	NTU	44	15	9.8 - 46	17	8.0	15 - 19
<b>TEST PERIOD 2</b>							
<b>Raw Water</b>							
pH		23	8.3	7.9 - 8.4	8.2	0.16	8.1 - 8.3
Desktop Turbidity	NTU	46	1.3	1.0 - 2.1	1.3	0.24	1.2 - 1.4
Temperature	degC	46	19	11 - 29	19	4.0	18 - 20
<b>Filtrate</b>							
Desktop Turbidity	NTU	23	0.05	0.05 - 0.05	0.05	0.00	0.05 - 0.05
<b>Backwash Waste</b>							
Turbidity	NTU	47	9.3	4.8 - 35	12	7.7	9.8 - 14

**Table 4-4. Summary of online particle and turbidity data for Ionics UF membrane system.**

Parameter	Unit	Count	Median	Range	Average	Standard Deviation	95 Percent Confidence Interval
<b>TEST PERIOD 1</b>							
<b>Raw Water</b>							
Turbidity	ntu	191	1.2	0.95 - 1.5	1.2	0.12	1.2 - 1.2
> 2 um Particles	#/mL	186	5200	4000 - 7200	5300	680	5200 - 5400
2-3 um Particles	#/mL	186	2700	2300 - 3500	2700	300	2700 - 2700
3-5 um Particles	#/mL	186	1600	1200 - 2300	1700	230	1700 - 1700
5-15 um Particles	#/mL	186	880	530 - 1400	900	170	880 - 920
5-7 um Particles	#/mL	186	550	360 - 850	570	100	560 - 580
7-10 um Particles	#/mL	186	240	130 - 390	250	49	240 - 260
10-15 um Particles	#/mL	186	85	40 - 200	85	20	82 - 88
>15 um Particles	#/mL	186	20	8.7 - 120	21	8.9	20 - 22
<b>Filtrate</b>							
Turbidity	ntu	186	0.05	0.05 - 0.10	0.05	0.0037	0.05 - 0.05
> 2 um Particles	#/mL	186	0.14	0.038 - 5.7	0.60	1.2	0.43 - 0.77
2-3 um Particles	#/mL	186	0.085	0.038 - 3.0	0.31	0.61	0.22 - 0.40
3-5 um Particles	#/mL	186	0.062	0.038 - 1.7	0.19	0.35	0.14 - 0.24
5-15 um Particles	#/mL	186	0.047	0.038 - 1.9	0.16	0.26	0.12 - 0.20
5-7 um Particles	#/mL	186	0.043	0.038 - 0.63	0.090	0.12	0.073 - 0.11
7-10 um Particles	#/mL	186	0.040	0.038 - 0.67	0.065	0.077	0.054 - 0.076
10-15 um Particles	#/mL	186	0.038	0.038 - 0.72	0.051	0.059	0.043 - 0.059
>15 um Particles	#/mL	186	0.038	0.038 - 0.33	0.043	0.026	0.039 - 0.047
Log Removal 2-3 um Particles		33	4.3	3.0 - 4.8	4.2	0.45	4.0 - 4.4
Log Removal 3-5 um Particles		33	4.3	3.0 - 4.6	4.2	0.40	4.1 - 4.3
Log Removal 5-15 um Particles		33	4.0	3.0 - 4.4	3.9	0.40	3.8 - 4.0
Log Removal 5-7 um Particles		33	4.0	3.0 - 4.2	3.9	0.30	3.8 - 4.0
Log Removal 7-10 um Particles		33	3.7	3.0 - 3.9	3.6	0.24	3.5 - 3.7
Log Removal 10-15 um Particles		33	3.3	2.8 - 3.4	3.2	0.18	3.1 - 3.3
Log Removal >15 um Particles		33	2.7	2.3 - 2.9	2.7	0.13	2.7 - 2.7

**Table 4-4. Continued.**

Parameter	Unit	Count	Median	Range	Average	Standard Deviation	95 Percent Confidence Interval
<b>TEST PERIOD 2</b>							
<b>Raw Water</b>							
Turbidity	ntu	187	1.2	0.95 - 2.5	1.3	0.21	1.3 - 1.3
> 2 um Particles	#/mL	187	4500	2400 - 7500	4500	920	4400 - 4600
2-3 um Particles	#/mL	187	2400	1400 - 3500	2400	410	2300 - 2500
3-5 um Particles	#/mL	187	1400	690 - 2400	1400	310	1400 - 1400
5-15 um Particles	#/mL	187	680	270 - 1500	680	200	650 - 710
5-7 um Particles	#/mL	187	440	180 - 900	430	120	410 - 450
7-10 um Particles	#/mL	187	180	66 - 410	180	59	170 - 190
10-15 um Particles	#/mL	187	63	32 - 170	67	22	64 - 70
>15 um Particles	#/mL	187	17	8.6 - 60	19	7.8	18 - 20
<b>Filtrate</b>							
Turbidity	ntu	187	0.05	0.05 - 0.05	0.05	0.00	0.05 - 0.05
> 2 um Particles	#/mL	187	1.4	0.50 - 11	2.1	1.6	1.9 - 2.3
2-3 um Particles	#/mL	187	0.69	0.28 - 5.4	1.2	0.86	1.1 - 1.3
3-5 um Particles	#/mL	187	0.39	0.15 - 3.4	0.63	0.46	0.56 - 0.70
5-15 um Particles	#/mL	187	0.28	0.11 - 2.3	0.37	0.24	0.34 - 0.40
5-7 um Particles	#/mL	187	0.14	0.063 - 1.3	0.20	0.14	0.18 - 0.22
7-10 um Particles	#/mL	187	0.081	0.044 - 0.62	0.10	0.063	0.091 - 0.11
10-15 um Particles	#/mL	187	0.052	0.040 - 0.38	0.062	0.031	0.058 - 0.066
>15 um Particles	#/mL	187	0.044	0.038 - 0.33	0.048	0.024	0.045 - 0.051
Log Removal 2-3 um Particles		32	3.5	2.9 - 3.9	3.4	0.30	3.3 - 3.5
Log Removal 3-5 um Particles		32	3.5	2.9 - 3.9	3.4	0.30	3.3 - 3.5
Log Removal 5-15 um Particles		32	3.3	2.8 - 3.7	3.3	0.24	3.2 - 3.4
Log Removal 5-7 um Particles		32	3.4	2.9 - 3.9	3.4	0.27	3.3 - 3.5
Log Removal 7-10 um Particles		32	3.3	2.8 - 3.7	3.3	0.23	3.2 - 3.4
Log Removal 10-15 um Particles		32	3.0	2.6 - 3.4	3.0	0.16	2.9 - 3.1
Log Removal >15 um Particles		32	2.6	2.2 - 2.9	2.6	0.15	2.5 - 2.7

**Table 4-5. Summary of microbial water quality analyses for the Ionics UF membrane system.**

Parameter	Unit	Count	Median	Range	Average	Standard Deviation	95 Percent Confidence Interval
<b>TEST PERIOD 1</b>							
<b>Raw Water</b>							
Total Coliforms	MPN/100mL	6	18	<2 - 80	<25	28	2.6 - 47
HPC	cfu/mL	6	95	2 - 120	83	42	49 - 120
<b>Filtrate</b>							
Total Coliforms	MPN/100mL	6	<2	<2 - <2	<2	0.00	<2 - <2
HPC	cfu/mL	6	105	11 - 140	100	46	63 - 140
<b>Backwash Waste</b>							
Total Coliforms	MPN/100mL	6	40	<2 - 130	<50	48	12 - 88
<b>TEST PERIOD 2</b>							
<b>Raw Water</b>							
Total Coliforms	MPN/100mL	4	6	<2 - 17	<7.7	6.7	1.1 - 14
HPC	cfu/mL	5	48	2 - 1400	310	610	0 - 840
<b>Filtrate</b>							
Total Coliforms	MPN/100mL	4	<2	<2 - <2	<2	0.00	<2 - <2
HPC	cfu/mL	5	200	48 - 580	200	210	16 - 380
<b>Backwash Waste</b>							
Total Coliforms	MPN/100mL	5	4	2 - 30	<10	12	0 - 21

Note: All calculations with below detection limit values used the detection limit value in the calculation as a conservative estimate.

**Table 4-6. Summary of general water quality analyses for the Ionics UF membrane system.**

Parameter	Unit	Count	Median	Range	Average	Standard Deviation	95 Percent Confidence Interval
<b>TEST PERIOD 1</b>							
<b>Raw Water</b>							
Alkalinity	mg/L as CaCO <sub>3</sub>	5	120	120 - 130	120	1.1	120 - 120
Total Hardness	mg/L as CaCO <sub>3</sub>	5	240	220 - 240	240	11	230 - 250
Calcium Hardness	mg/L as CaCO <sub>3</sub>	4	150	140 - 160	150	6.6	140 - 160
Total Suspended Solids	mg/L	5	10	1.8 - 15	8.0	5.5	3.2 - 13
Total Dissolved Solids	mg/L	5	500	490 - 500	500	6.4	490 - 510
TOC	mg/L	5	3.1	2.5 - 4.1	3.2	0.7	2.6 - 3.8
UV254 Unfiltered	/cm	5	0.07	0.06 - 0.1	0.07	0.02	0.05 - 0.09
UV254 Filtered	/cm	5	0.06	0.05 - 0.06	0.06	0.003	0.06 - 0.06
<b>Filtrate</b>							
Alkalinity	mg/L as CaCO <sub>3</sub>	5	120	120 - 120	120	0.00	120 - 120
Total Hardness	mg/L as CaCO <sub>3</sub>	5	230	220 - 240	230	8.5	220 - 240
Calcium Hardness	mg/L as CaCO <sub>3</sub>	5	150	140 - 150	150	5.1	150 - 150
Total Suspended Solids	mg/L	5	<1.0	<1.0 - <1.0	<1.0	0.00	<1.0 - <1.0
Total Dissolved Solids	mg/L	5	500	490 - 510	500	8.7	490 - 510
TOC	mg/L	5	2.5	2.4 - 2.6	2.5	0.09	2.4 - 2.6
UV254 Unfiltered	/cm	5	0.06	0.05 - 0.06	0.06	0.003	0.06 - 0.06
<b>Backwash Waste</b>							
Total Suspended Solids	mg/L	5	25	16 - 68	32	21	14 - 50
<b>TEST PERIOD 2</b>							
<b>Raw Water</b>							
Alkalinity	mg/L as CaCO <sub>3</sub>	6	120	120 - 120	120	1.9	120 - 120
Total Hardness	mg/L as CaCO <sub>3</sub>	6	220	210 - 220	220	6.4	210 - 230
Calcium Hardness	mg/L as CaCO <sub>3</sub>	6	140	130 - 140	140	4.7	140 - 140
Total Suspended Solids	mg/L	5	5.9	3.9 - 20	9.4	7.0	3.3 - 16
Total Dissolved Solids	mg/L	6	470	460 - 480	470	7.4	460 - 480
TOC	mg/L	6	3.6	2.9 - 4.0	3.6	0.4	3.3 - 3.9
UV254 Unfiltered	/cm	6	0.08	0.07 - 0.09	0.08	0.007	0.07 - 0.09
UV254 Filtered	/cm	6	0.07	0.06 - 0.08	0.07	0.005	0.07 - 0.07
<b>Filtrate</b>							
Alkalinity	mg/L as CaCO <sub>3</sub>	5	120	120 - 120	120	1.3	120 - 120
Total Hardness	mg/L as CaCO <sub>3</sub>	5	220	210 - 230	220	6.8	210 - 230
Calcium Hardness	mg/L as CaCO <sub>3</sub>	5	130	130 - 140	140	6.4	130 - 150
Total Suspended Solids	mg/L	3	<1.0	<1.0 - <1.0	<1.0	0.00	<1.0 - <1.0
Total Dissolved Solids	mg/L	5	470	470 - 480	470	3.9	470 - 470
TOC	mg/L	5	3.8	3.5 - 4.3	3.9	0.3	3.6 - 4.2
UV254 Unfiltered	/cm	5	0.07	0.06 - 0.08	0.07	0.007	0.06 - 0.08
<b>Backwash Waste</b>							
Total Suspended Solids	mg/L	4	9.8	1.0 - 13	8.5	5.4	3.2 - 14

Note: All calculations with below detection limit values used the detection limit value in the calculation as a conservative estimate.  
All results rounded to two significant digits with the exception of UV254, which is rounded to one significant digit.

**Table 4-7. Comparison of calculated and measured total suspended solids for Ionics UF membrane system.**

Date	Filtration Filtrate Flow (gpm)	Cycle Length (min)	Volume Filtered (gal)	"B" Fast Flush Volume (gal)	"B" Reverse Flow Volume (gal)	Measured Raw TSS (mg/L)	Measured Backwash TSS (mg/L)	Calculated Backwash TSS 1st Cycle (mg/L)	Calculated Backwash TSS 9th Cycle (mg/L)
<b>TEST PERIOD 1</b>									
12/8/99	21	30	630	30	15	2.8	20.2	14	20
12/14/99	21	30	630	30	15	14.6	25	71	106
12/20/99	21	30	630	30	15	10.4	15.8	51	76
12/27/99	21	30	630	30	15	1.8	67.6	9	13
1/10/00	21	30	630	30	15	10.3	32	50	75
<b>TEST PERIOD 2</b>									
3/8/00	21	30	630	6.5	45	12.7	13.4	88	172
3/15/00	21	30	630	6.5	45	3.9	1	27	53
3/22/00	21	30	630	6.5	45	4.2	8.45	29	57
4/5/00	21	30	630	6.5	45	5.9	11.2	41	80

Note: For both Test Periods, 9 "B" backwashes were performed, followed by a "C" backwash.

**Table 4-8. Feed and filtrate concentrations of MS2 virus for the Ionics UF membrane system.**

**Seeding #1**

Seeding Date: 1/12/00

Specific Flux at 20 degC = 4.9 gfd/psi (119 L/hr-m2-bar)

Feed Conc. (pfu/100mL)	Filtrate Conc. (pfu/100mL)	Log Removal	Backwash Waste Conc. (pfu/100mL)
7.6E+6	7.1E+2	4.0	
7.4E+6	2.0E+2	4.6	
2.8E+7	2.1E+2	5.1	4.7E+7
1.9E+7	3.4E+1	5.7	
2.8E+7	5.7E+1	5.7	
7.6E+6	1.7E+2	4.7	5.2E+7

**Seeding #2**

Seeding Date: 3/6/00

Specific Flux at 20 degC = 6.2 gfd/psi (152 L/hr-m2-bar)

Feed Conc. (pfu/100mL)	Filtrate Conc. (pfu/100mL)	Log Removal	Backwash Waste Conc. (pfu/100mL)
3.6E+7	3.1E+4	3.1	
3.9E+7	3.5E+3	4.0	
6.0E+7	2.9E+3	4.3	2.7E+8
4.0E+7	4.9E+4	2.9	
3.5E+7	4.4E+3	3.9	
4.2E+7	3.1E+3	4.1	1.2E+8

**Table 4-9. Review of manufacturer’s operations and maintenance manual for the Ionics UF membrane system.**

O & M Manual	Grade	Comment
Overall Organization	+	<ul style="list-style-type: none"> <li>The O&amp;M manual is very well organized. The table of contents includes the following main sections: Introduction, Safety Procedures, Equipment Description, Unit Installation, Start-up and Shut Down Procedures, Operation Instructions, Maintenance and Repair and Troubleshooting.</li> <li>The manual also includes the following appendices: Definition of terms and abbreviations, calculations, consumable material information, system drawings, PLC program, bill of materials and complete manufacturers literature for every purchased component on the system.</li> </ul>
Operations Sections	+	<ul style="list-style-type: none"> <li>Includes start up procedures section describing position of all manual valves during system operation. Includes detailed step by step instruction for both initial start up and normal start up after brief shutdown. Initial startup includes section detailing preliminary checks which should be made before start up.</li> <li>Shut down procedures sections include normal shutdown for events such as maintenance or long term storage, and emergency shutdown procedures. Also includes section on long term shutdown of unit.</li> <li>Operations section includes operations constraints section listing feed requirements, operating limits including operational feed pressure, TMP, pH range, and air scrub pressure. Another section describes both “B” and “C” backwash sequences, and finally a section describes the integrated integrity test which can be performed automatically as part of the “C” backwash sequence.</li> <li>The operations section also includes sections on alarms, control logic with tables showing position of all automatic valves during each phase of filtration and backwash modes, operator interface section with detailed descriptions of all screens on the Allen Bradley PLC.</li> <li>The operations sections are extremely well organized and make excellent use of tables and graphics.</li> </ul>
Maintenance Section	+	<ul style="list-style-type: none"> <li>Includes sections detailing daily, weekly, monthly and quarterly, yearly and 5-year maintenance checks.</li> <li>Maintenance sections discussed include UF Clean-In-Place and loading UF elements.</li> </ul>

**Table 4-9. Continued.**

O & M Manual	Grade	Comment
Troubleshooting	-	<ul style="list-style-type: none"> <li>Manual does not include a troubleshooting section with description of all alarm conditions and tables for each alarm condition detailing possible causes and solutions.</li> </ul>
Ancillary Equipment Information	+	<ul style="list-style-type: none"> <li>Equipment manufacturers' literature included as an appendix for all system components.</li> </ul>
Drawings and Schematics	+	<ul style="list-style-type: none"> <li>Overall makes good use of drawings and schematics.</li> <li>Should include process schematics showing water flow during filtration and backwash.</li> <li>Includes schematics of the Allen Bradley PanelView display and all associated screens.</li> </ul>
Use of Tables	+	<ul style="list-style-type: none"> <li>Manual makes very good use of tables to organize and present information.</li> </ul>
OVERALL COMMENT	+	<ul style="list-style-type: none"> <li>An excellent O&amp;M manual. It is very well organized, well written, clear and complete. An excellent table of contents makes locating information in the manual a simple process.</li> <li>The manual includes a good use of graphics to assist the reader's understanding.</li> <li>The manual includes as an appendix a list of components used on the Ionics UF unit, such as pumps, flow meters, valves and pressure gauges including manufacturer and model number.</li> </ul>

**Table 4-10. Efficiency of the Ionics UF membrane system.**

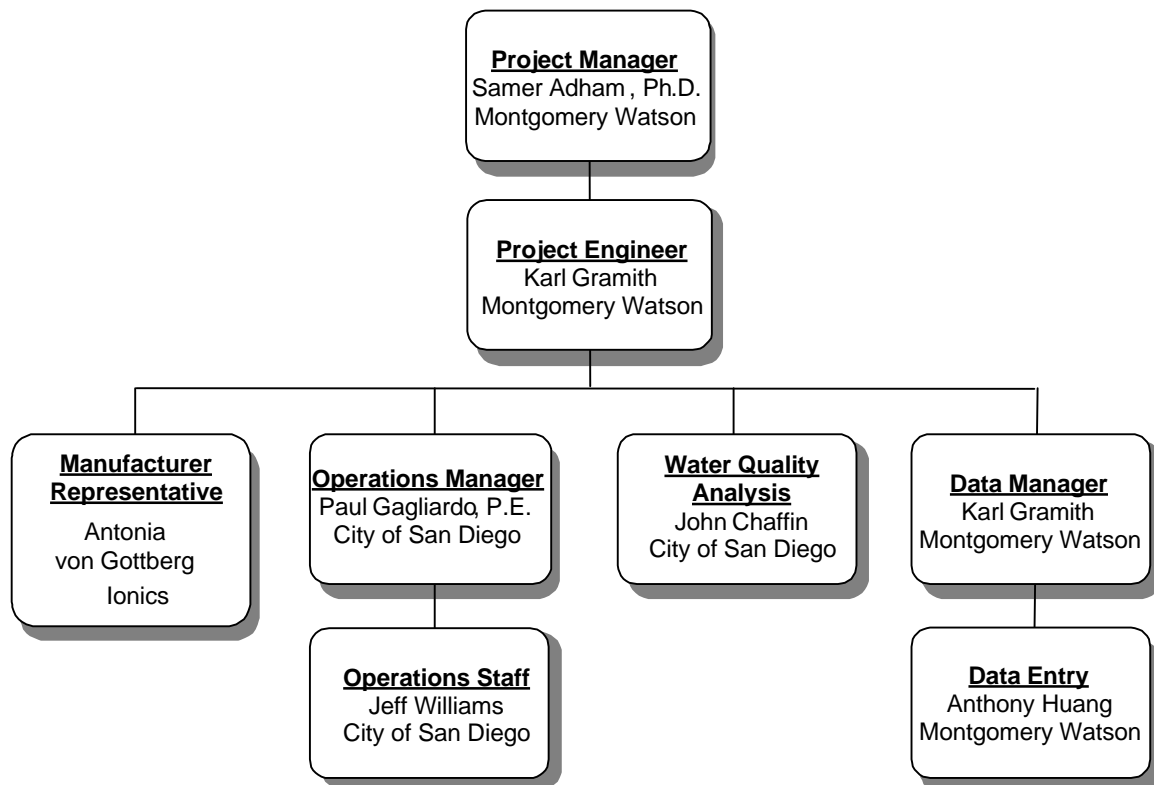
Parameter	Unit	Value
<b>ELECTRICAL USE</b>		
Voltage	Volt - three phase	460
Feed Pump Current	Amp	0.5
Feed Pump Power	Watt	420
<b>WATER PRODUCTION</b>		
Transmembrane Pressure	psi	9.3
	pascal	6.4E+04
Flow Rate	gpm	21
	m <sup>3</sup> /s	1.3E-03
Power	Watt	85
<b>EFFICIENCY</b>	<b>%</b>	<b>20%</b>

**Table 4-11. Chemical consumption for the Ionics UF membrane system.**

	Unit	Value
<b>Backwash Chlorine <sup>[1]</sup></b>		
Average Chlorine Dose	mg/L	8.7
Stock Chlorine Concentration	%	10
Average Backwash Volume	gal (L)	29 (110)
Chlorine Stock Volume per Backwash	mL	9.6
Backpulse Per Day	#	48
Stock Chlorine Use Per Day	gal (L)	0.12 (0.46)
<b>Cleaning Chemicals <sup>[2]</sup></b>		
Citric Acid 2%	lb (kg)	17 (7.7)
RO Clean L211	gal (L)	1.8 (7.0)
Acid Rinse pH 2 (Hydrochloric Acid)	gal (L)	0.053 (0.20)

<sup>[1]</sup> Based on average chlorine dose and average backwash volume

<sup>[2]</sup> Chemical use per cleaning

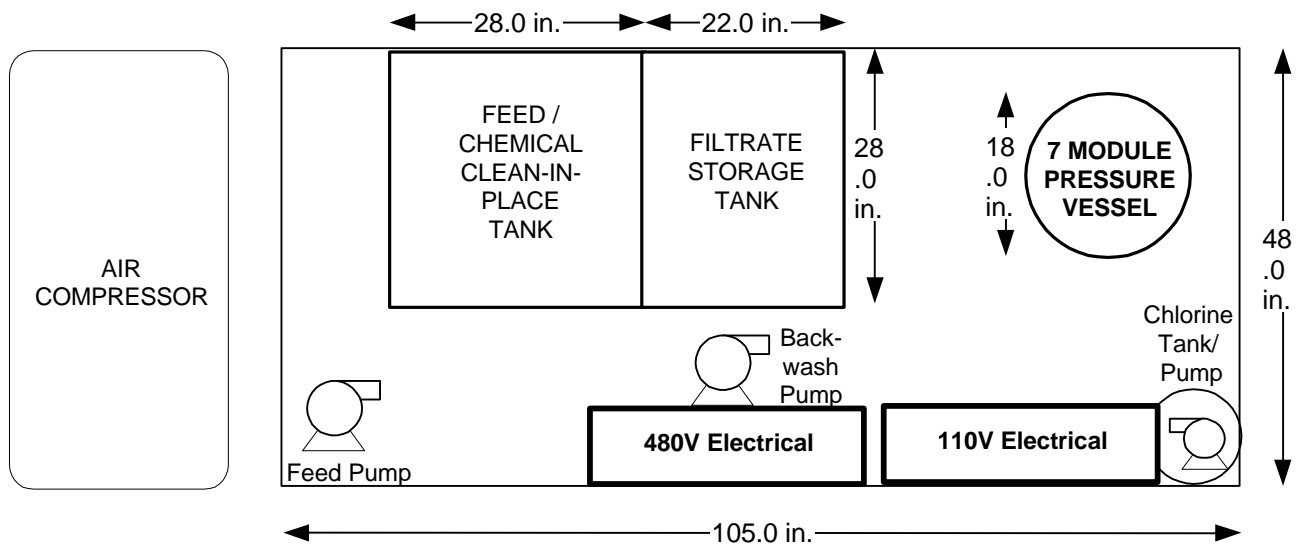


**Figure 1-1. Organizational chart showing lines of communication.**



**Figure 2-1. Photographs of ETV test unit.**

## PLAN VIEW



## SIDE VIEW

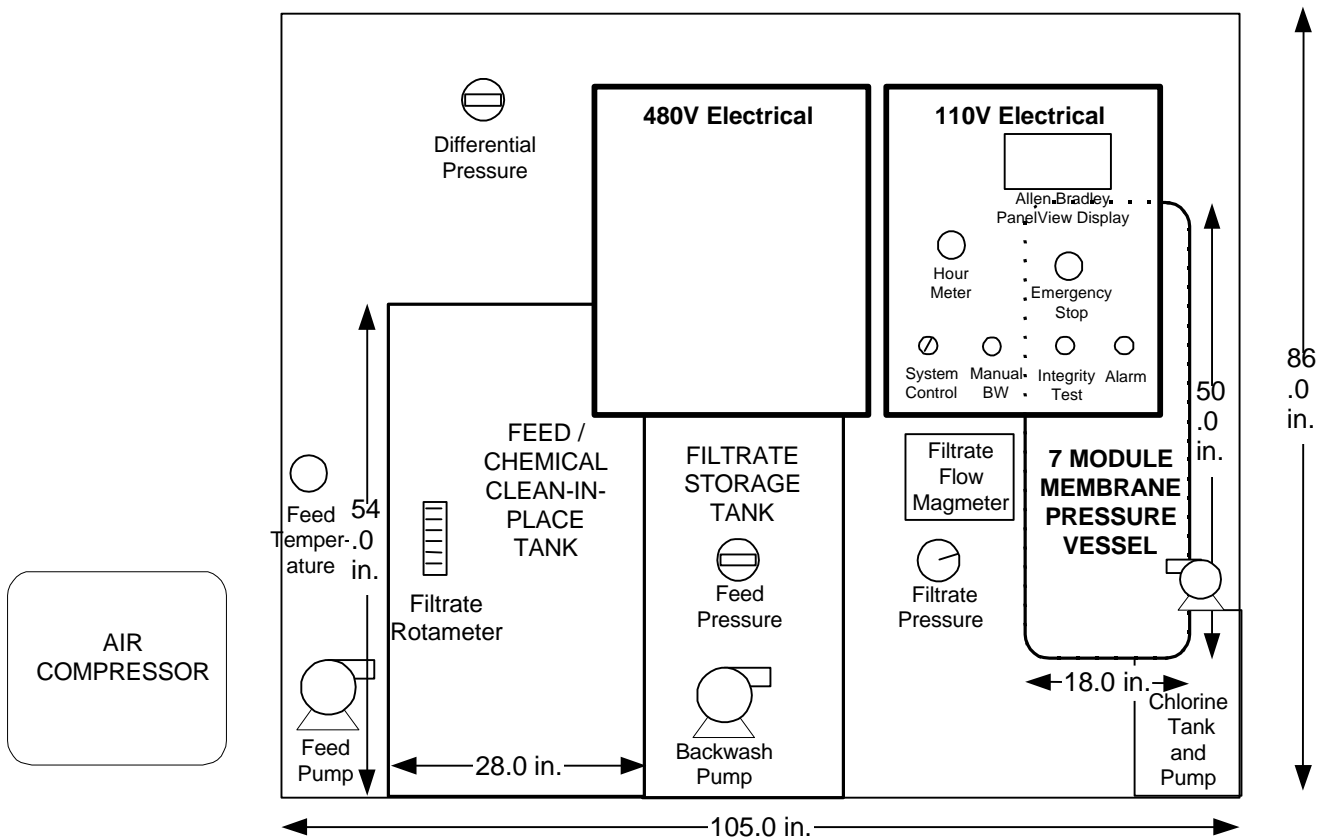
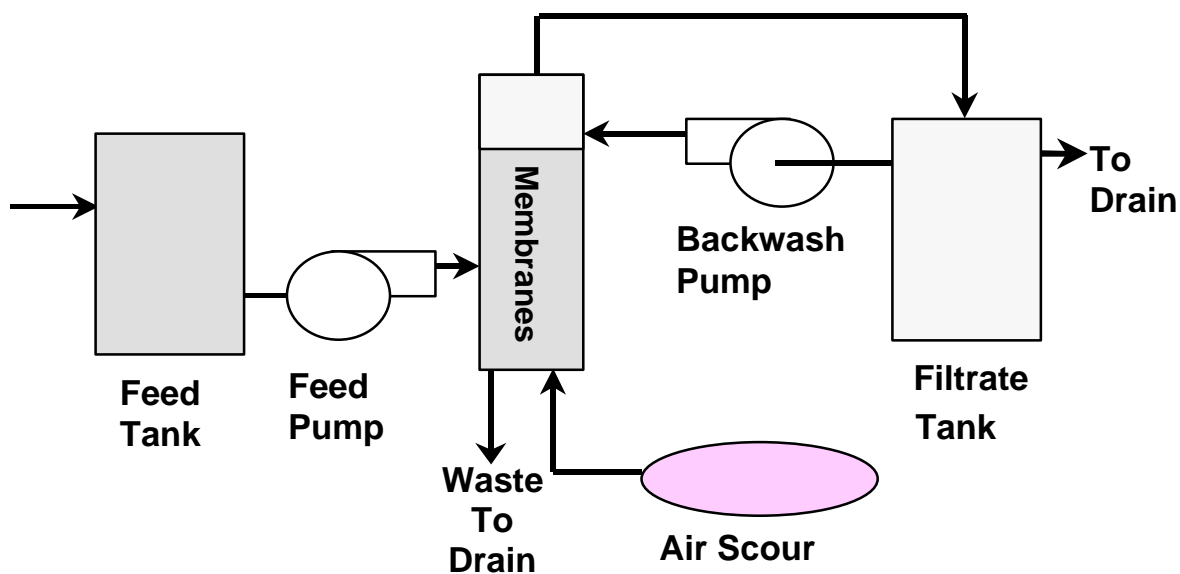


Figure 2-2. Spatial requirements for the Ionics UF unit.



**Figure 2-3. Schematic diagram of the Ionics UF membrane process.**

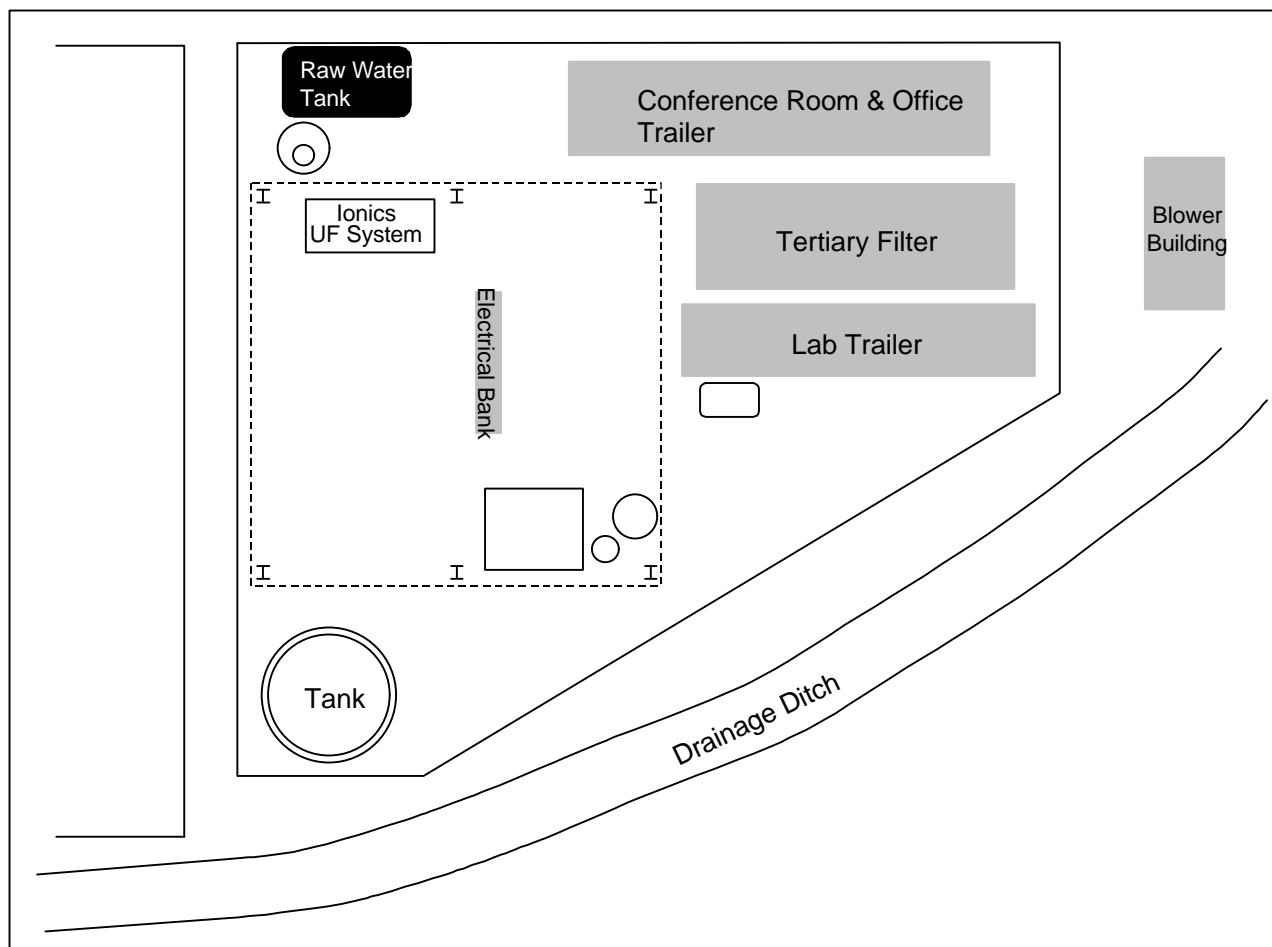


Figure not drawn to scale.

**Figure 3-1. Schematic of Aqua 2000 Research Center test site.**

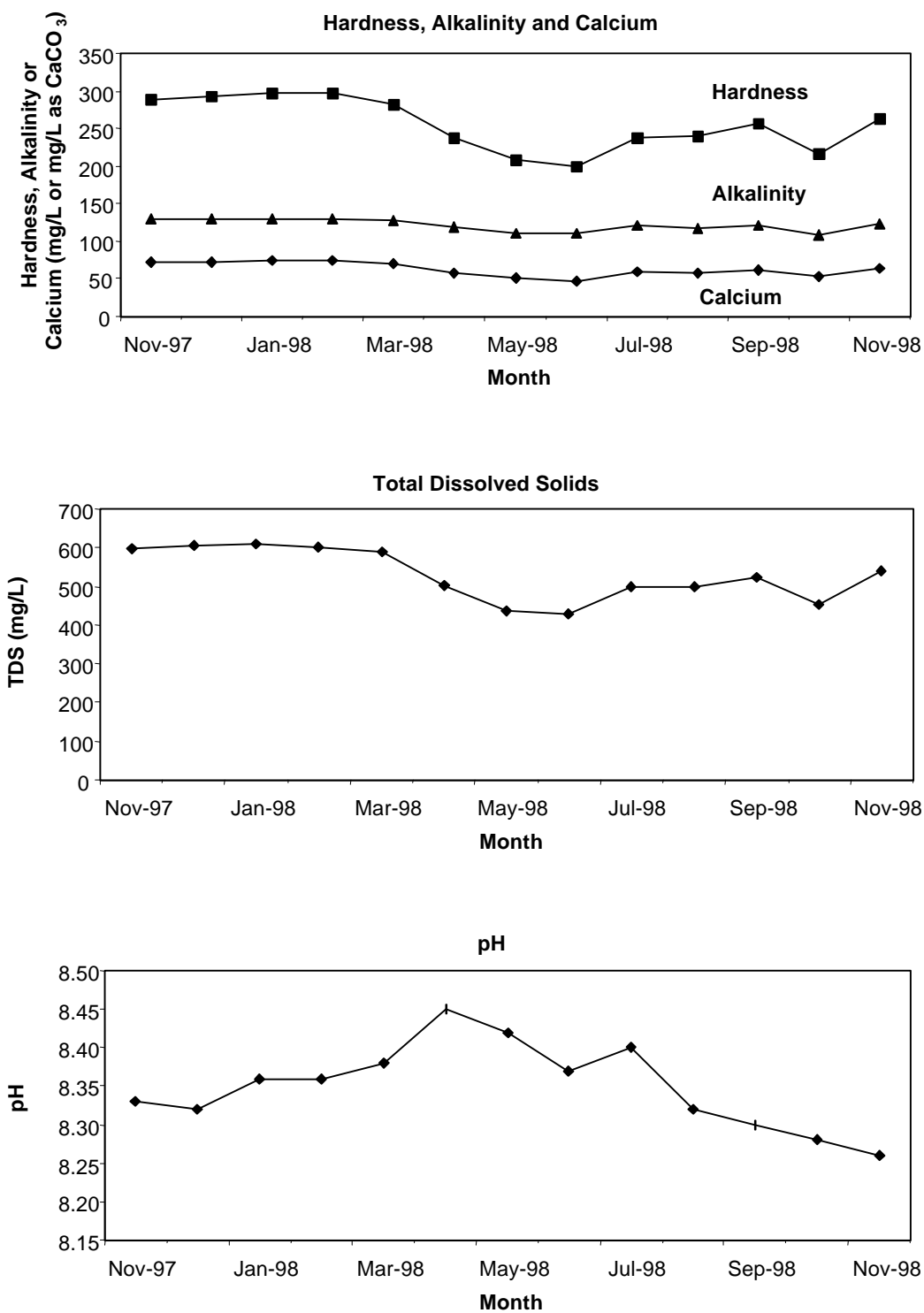
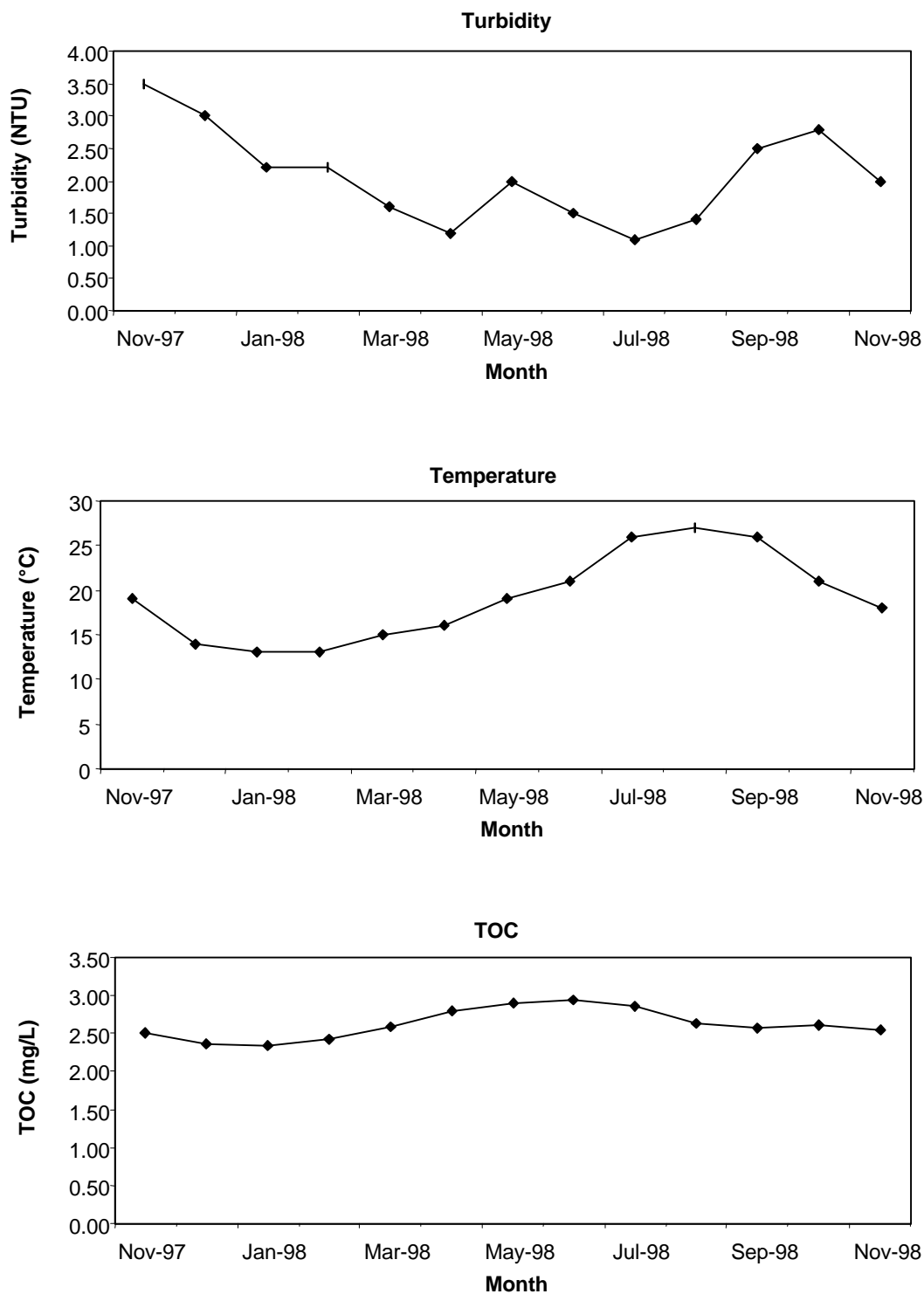
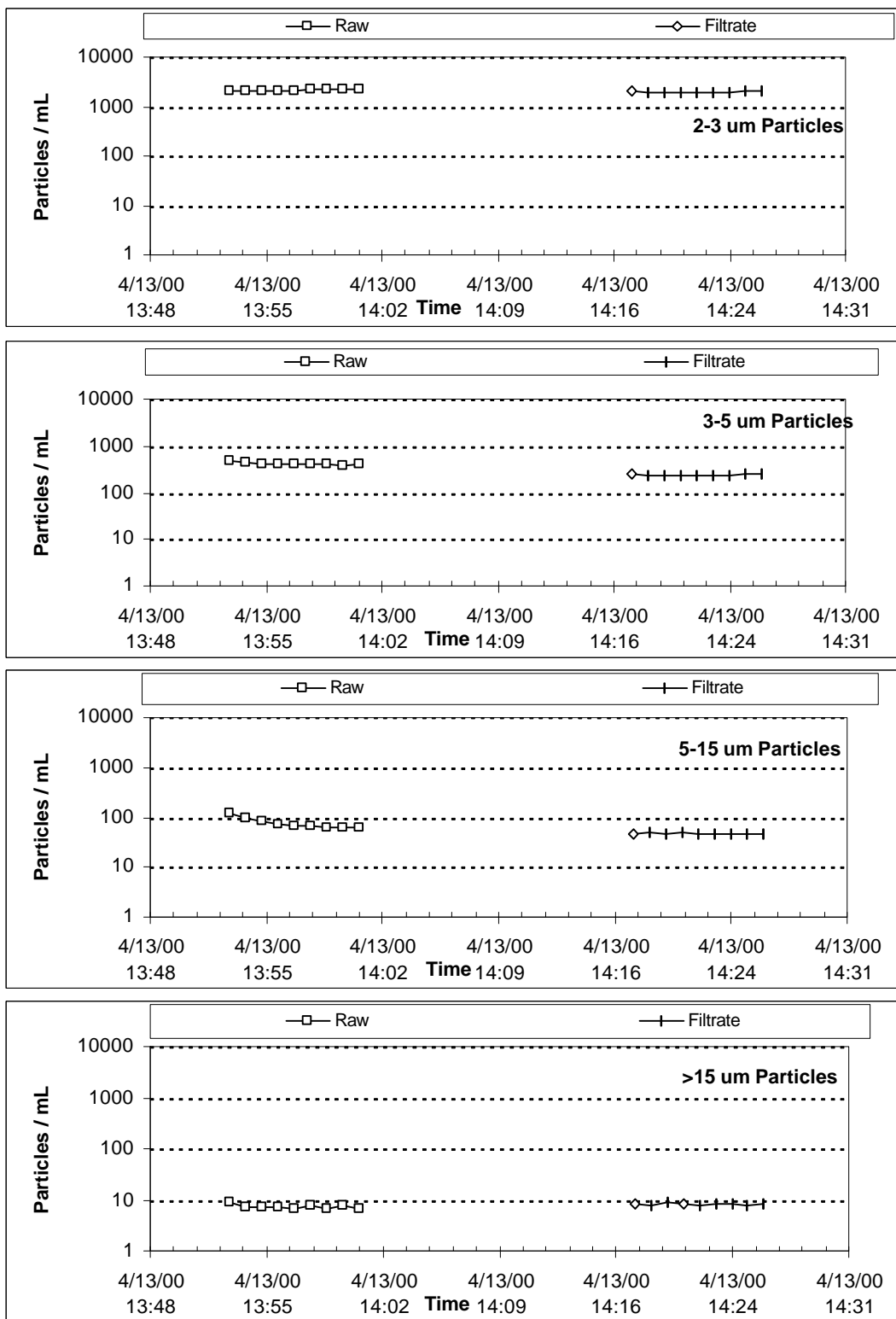

















Figure 3-2. Lake Skinner raw water quality.



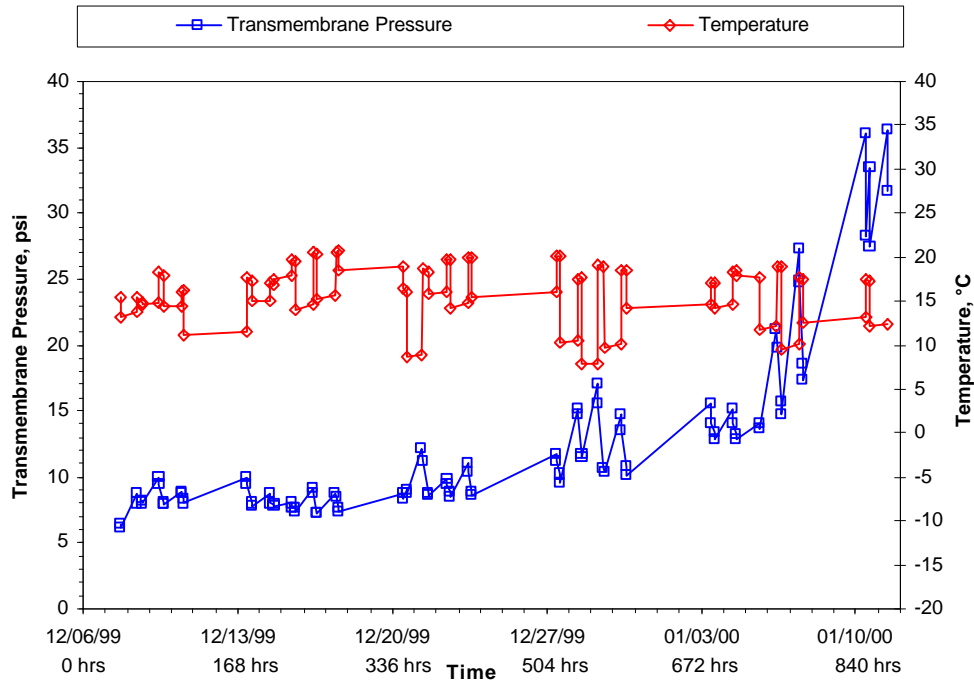
**Figure 3-3. Lake Skinner raw water quality.**



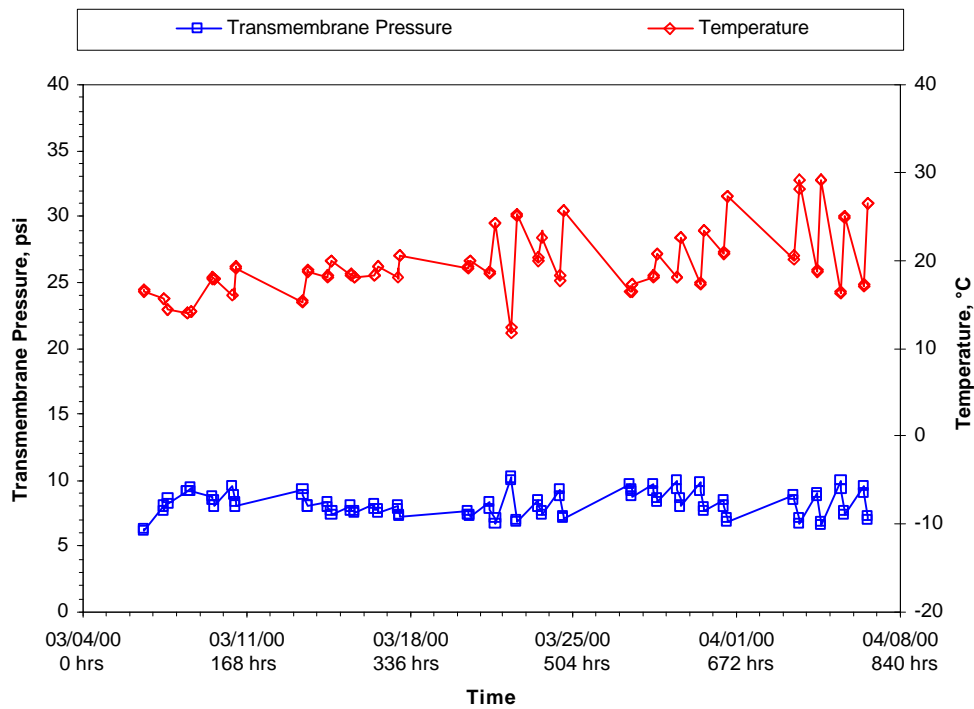
**Figure 3-4. Response of online particle counters to Duke Monosphere solution.**

Year	1999	2000											
Month	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Task 1: Membrane Flux & Recovery													
Task 2: Cleaning Efficiency													
Task 3: Finished Water Quality													
Task 4: Reporting of Membrane Pore Size													
Task 5: Membrane Integrity													
Task 6: Data Management													
Task 7: QA/QC													
Task 8: Microbial Removal													

**Figure 3-5. Membrane verification testing schedule.**

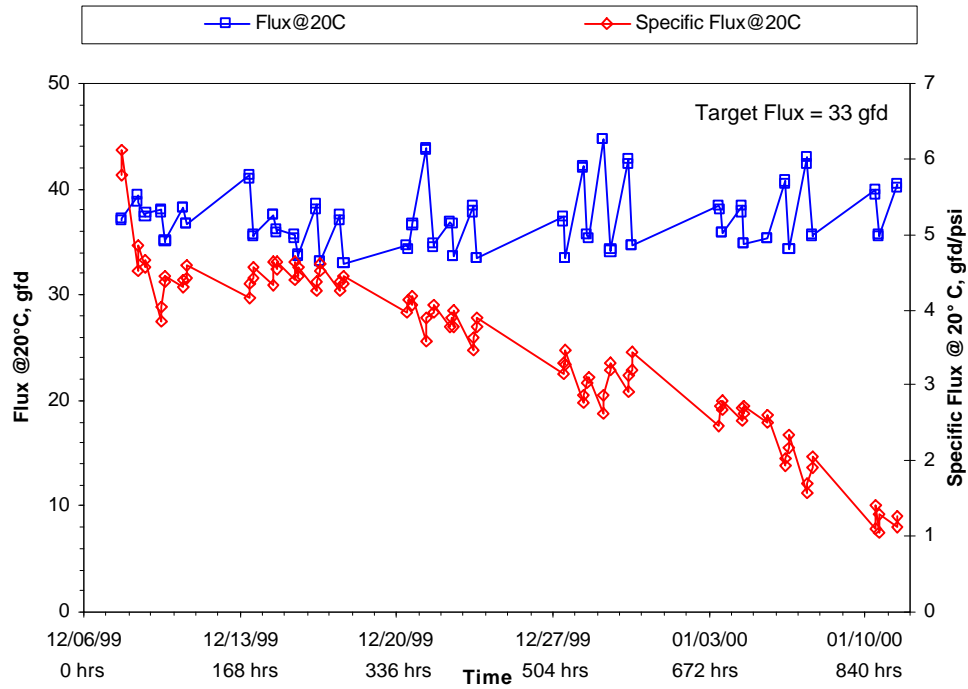


A – Test Period 1.

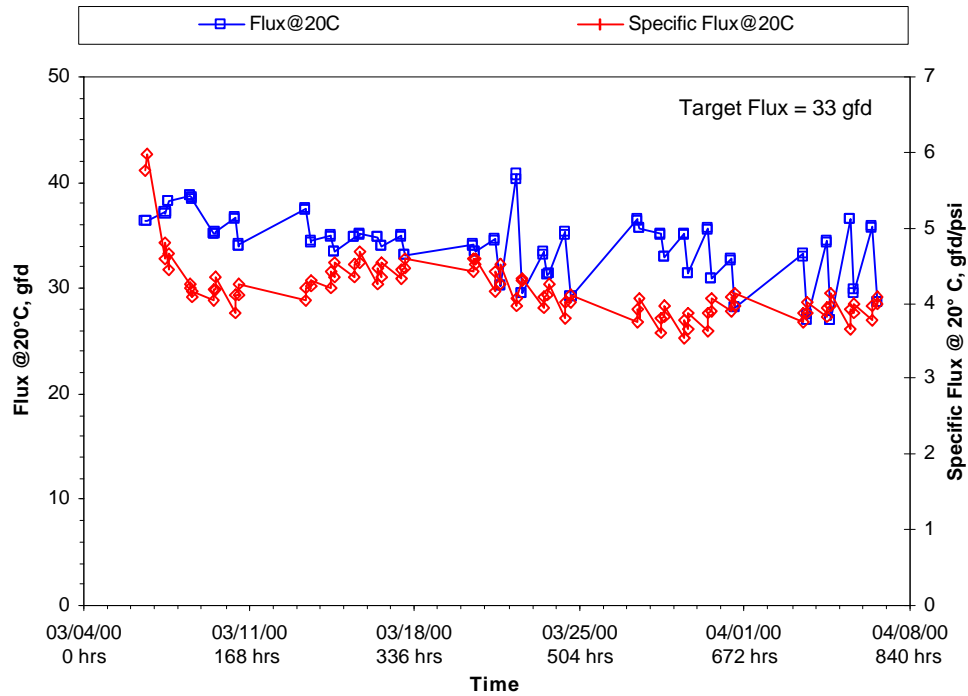


B – Test Period 2.

**Figure 4-1. Transmembrane pressure and temperature profiles for the Ionics UF membrane system.**

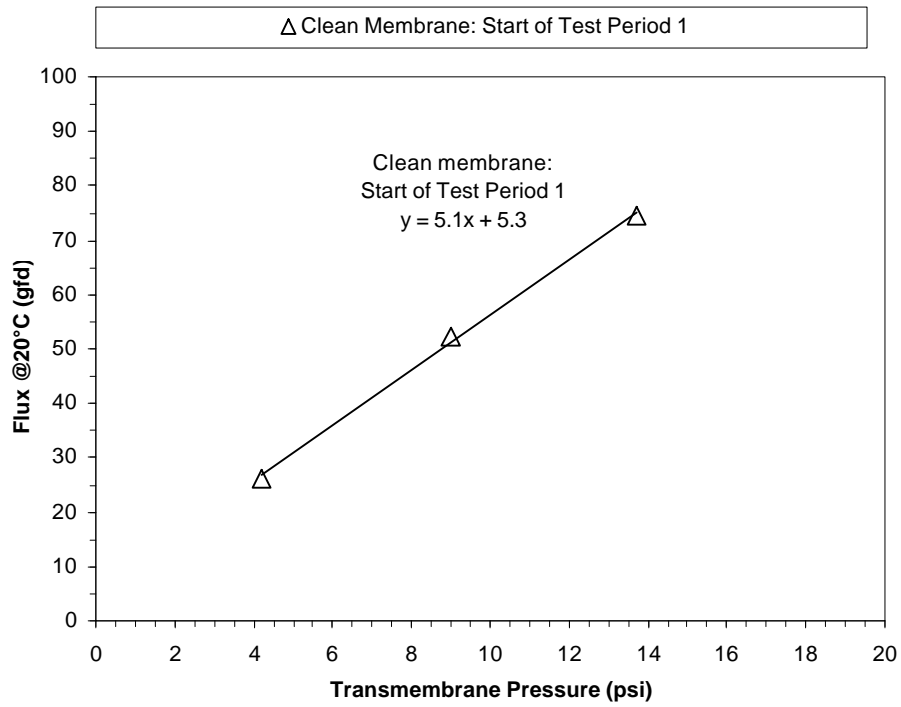


A – Test Period 1.

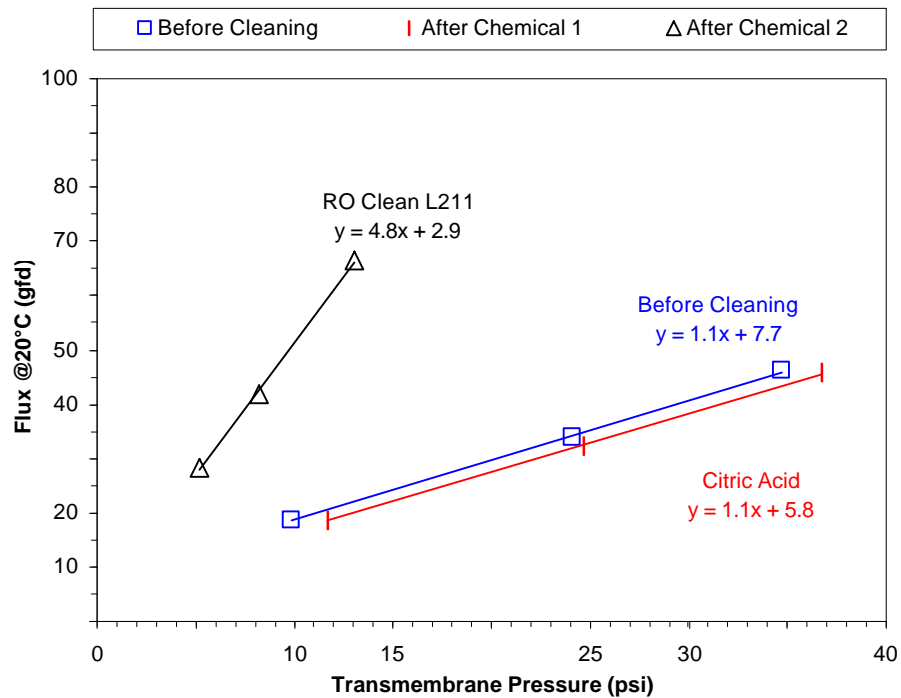


B – Test Period 2.

Figure 4-2. Operational flux and specific flux profiles for the Ionics UF membrane system.

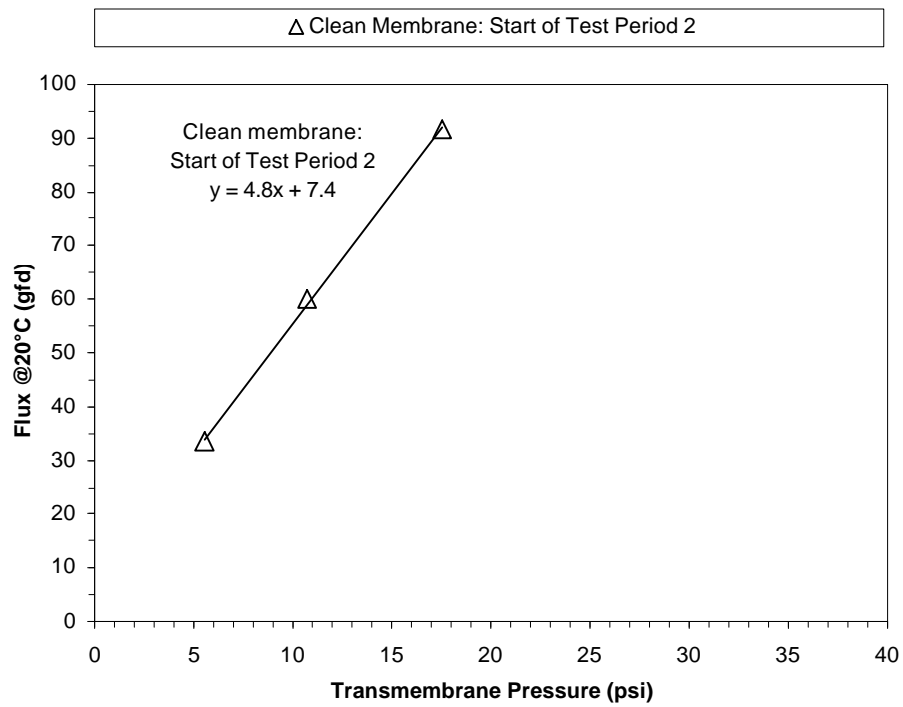


A – Clean membrane: start of Test Period 1.

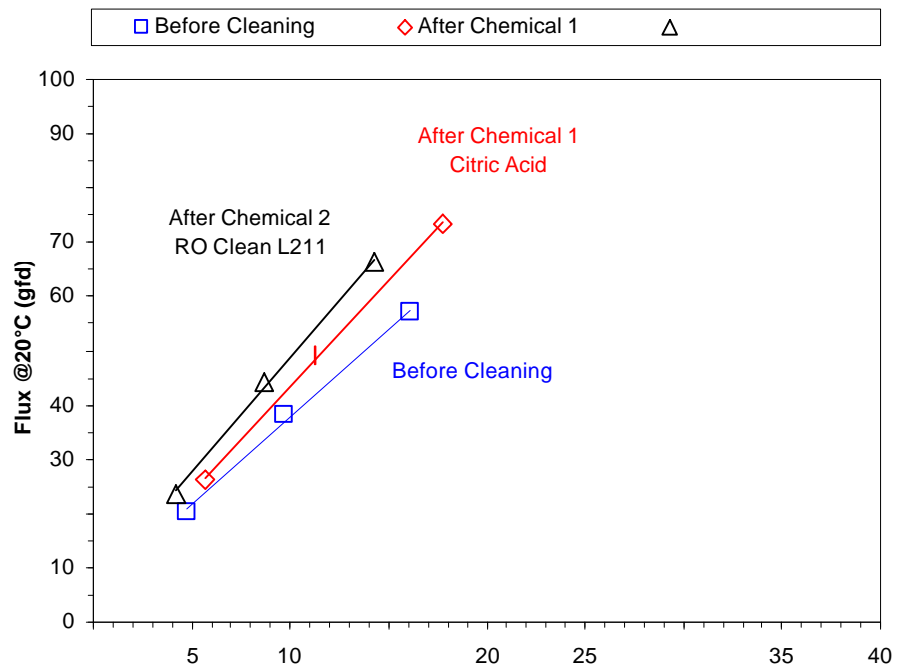


B – Test Period 1: cleaning 1-1 (1/11/00).

**Figure 4-3. Clean water flux profile during membrane chemical cleanings – Test Period 1.**

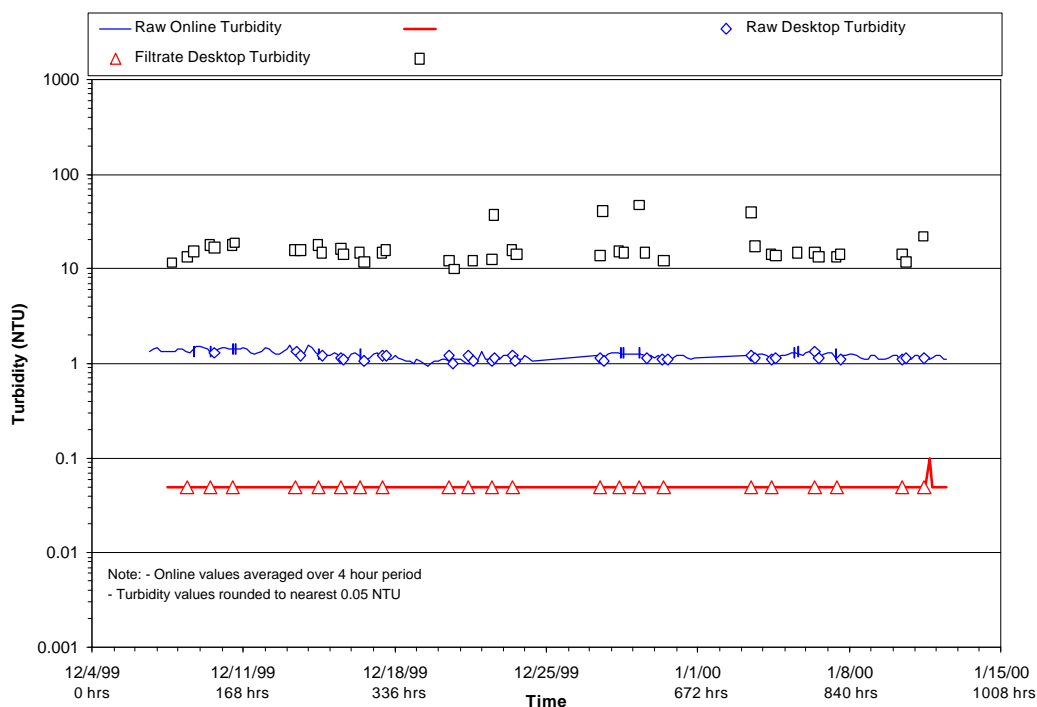


A – Clean membrane: start of Test Period 2.

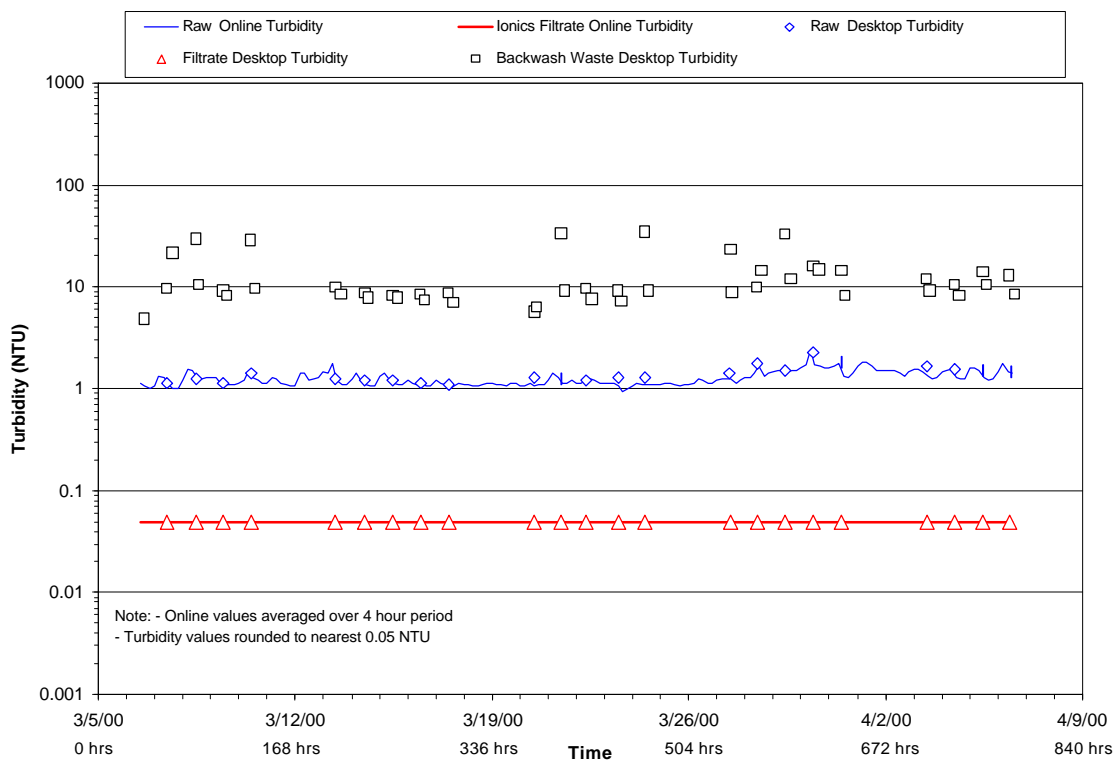


B – Test Period 2: cleaning 2-1 (4/7/00).

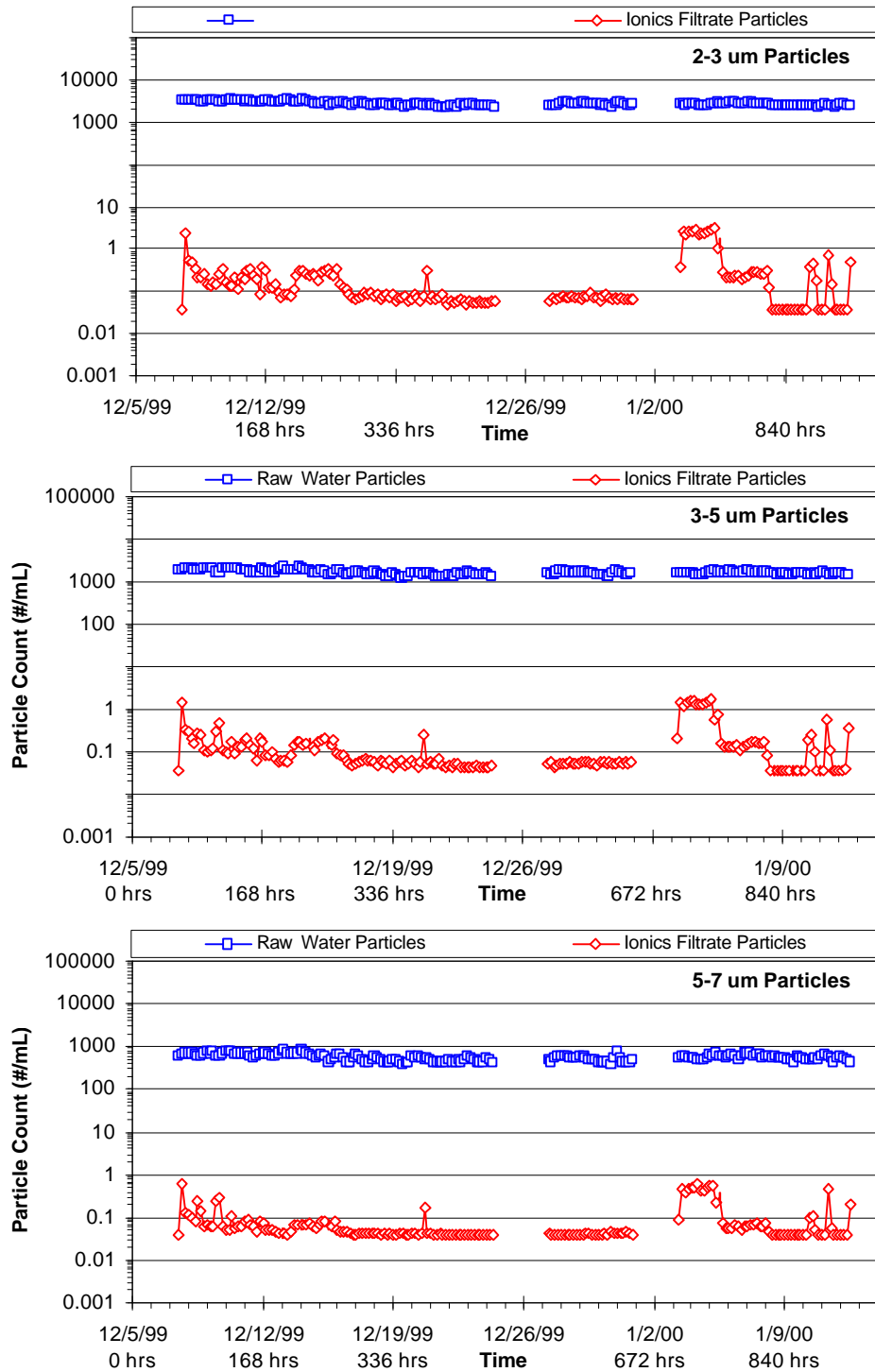
**Figure 4-4. Clean water flux profile during membrane chemical cleanings – Test Period 2.**



**Figure 4-5. Turbidity profile for raw water and Ionics UF membrane system – Test Period 1.**

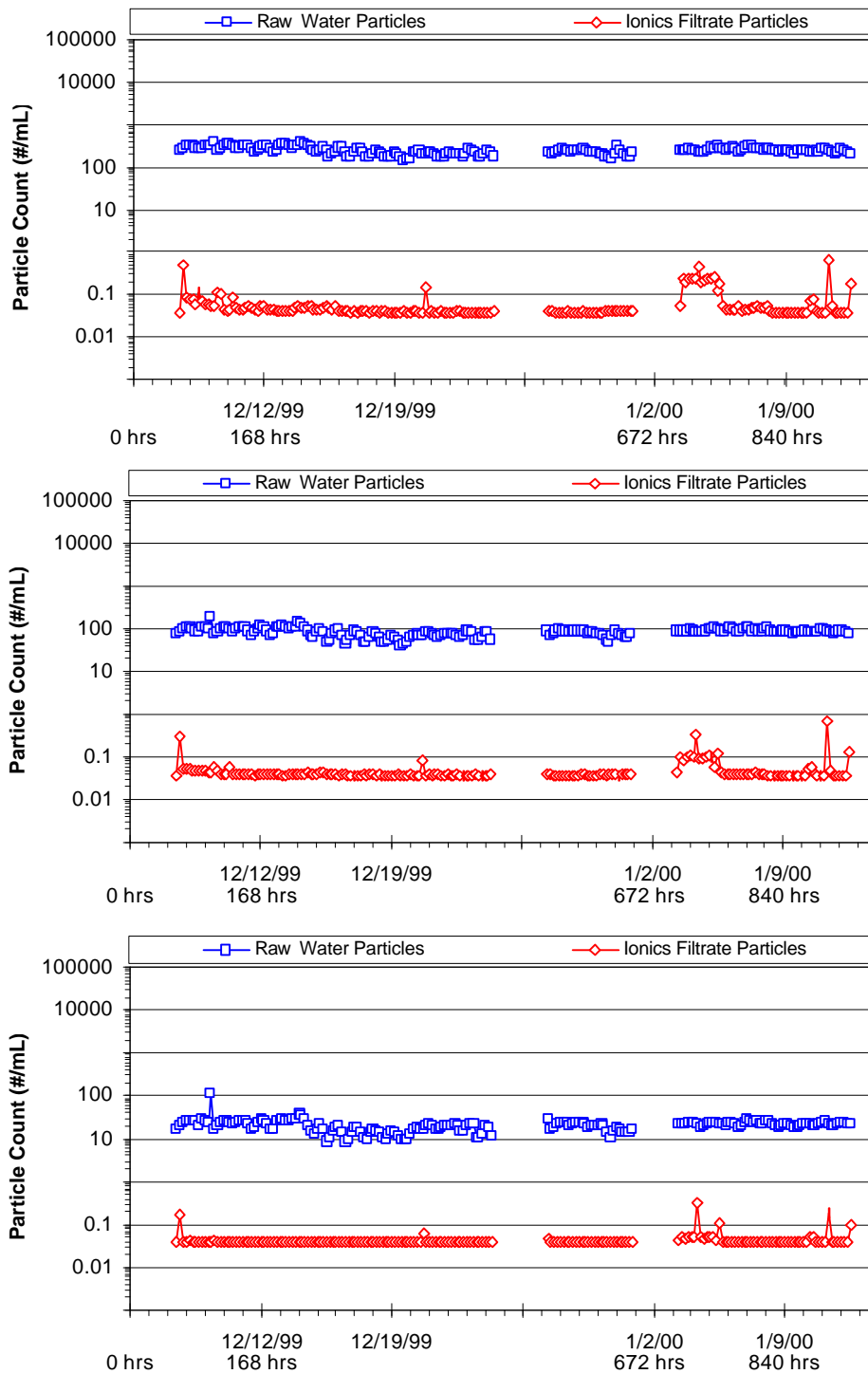


**Figure 4-6. Turbidity profile for raw water and Ionics UF membrane system – Test Period 2.**



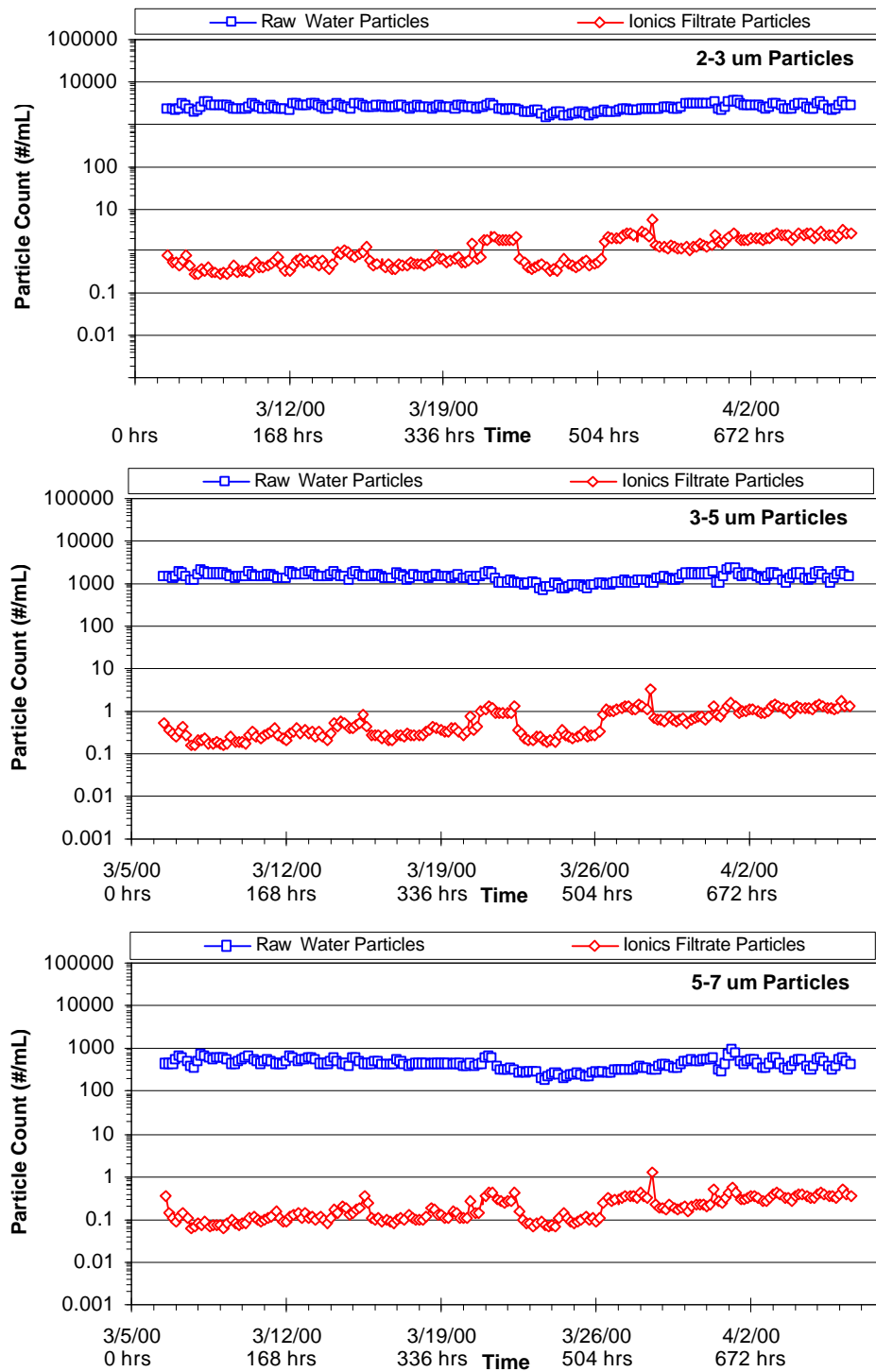
Note: Gap in data at 12/25/99 due to electrical outage of particle counters.  
Gap in data at 1/1/00 due to Y2K software failure.

**Figure 4-7. Particle counts for raw water and Ionics filtrate – Test Period 1.**



Note: Gap in data at 12/25/99 due to electrical outage of particle counters.  
Gap in data at 1/1/00 due to Y2K software failure.

**Figure 4-7. Continued.**



**Figure 4-8. Particle counts for raw water and Ionics filtrate – Test Period 2.**

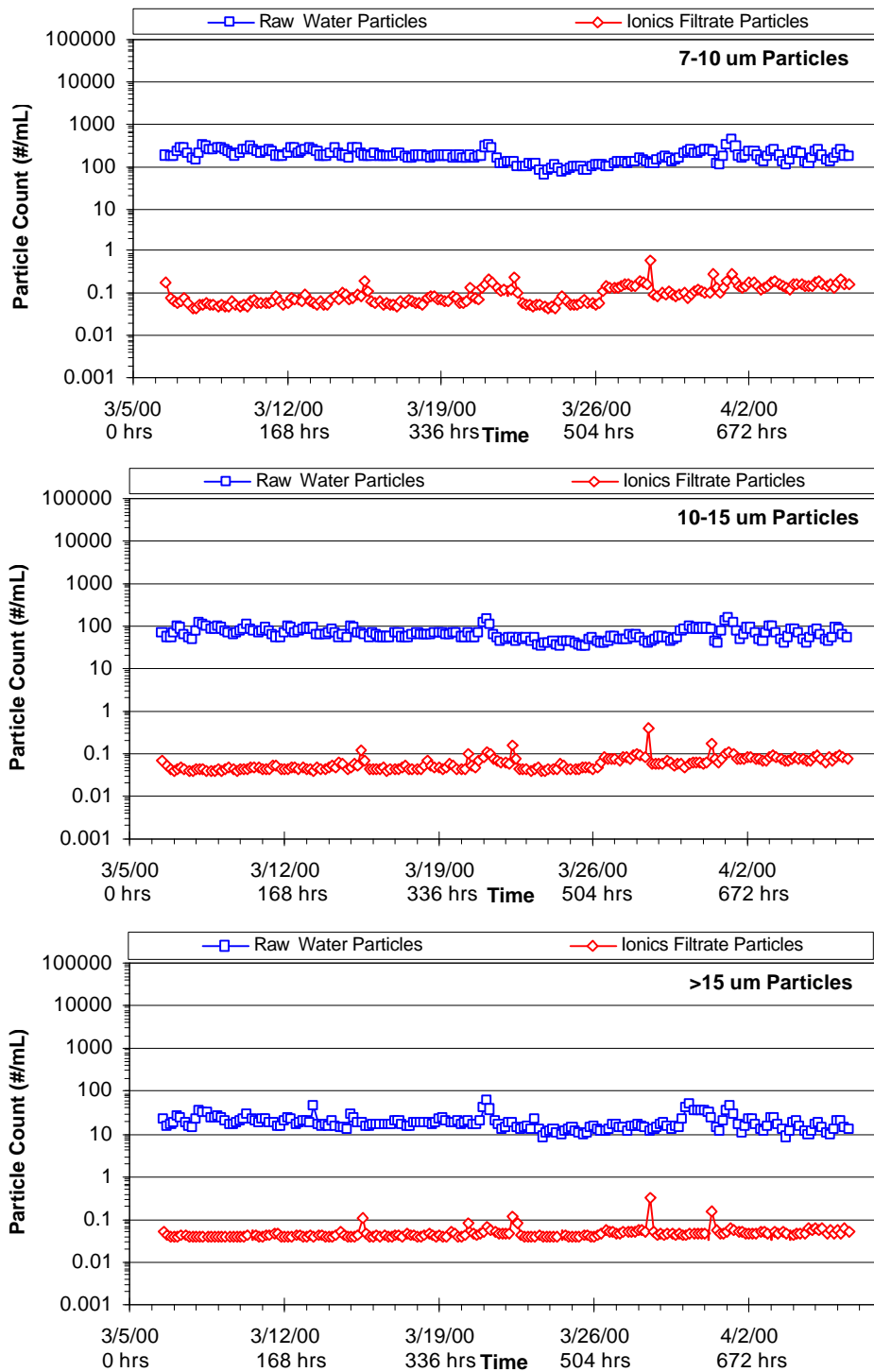
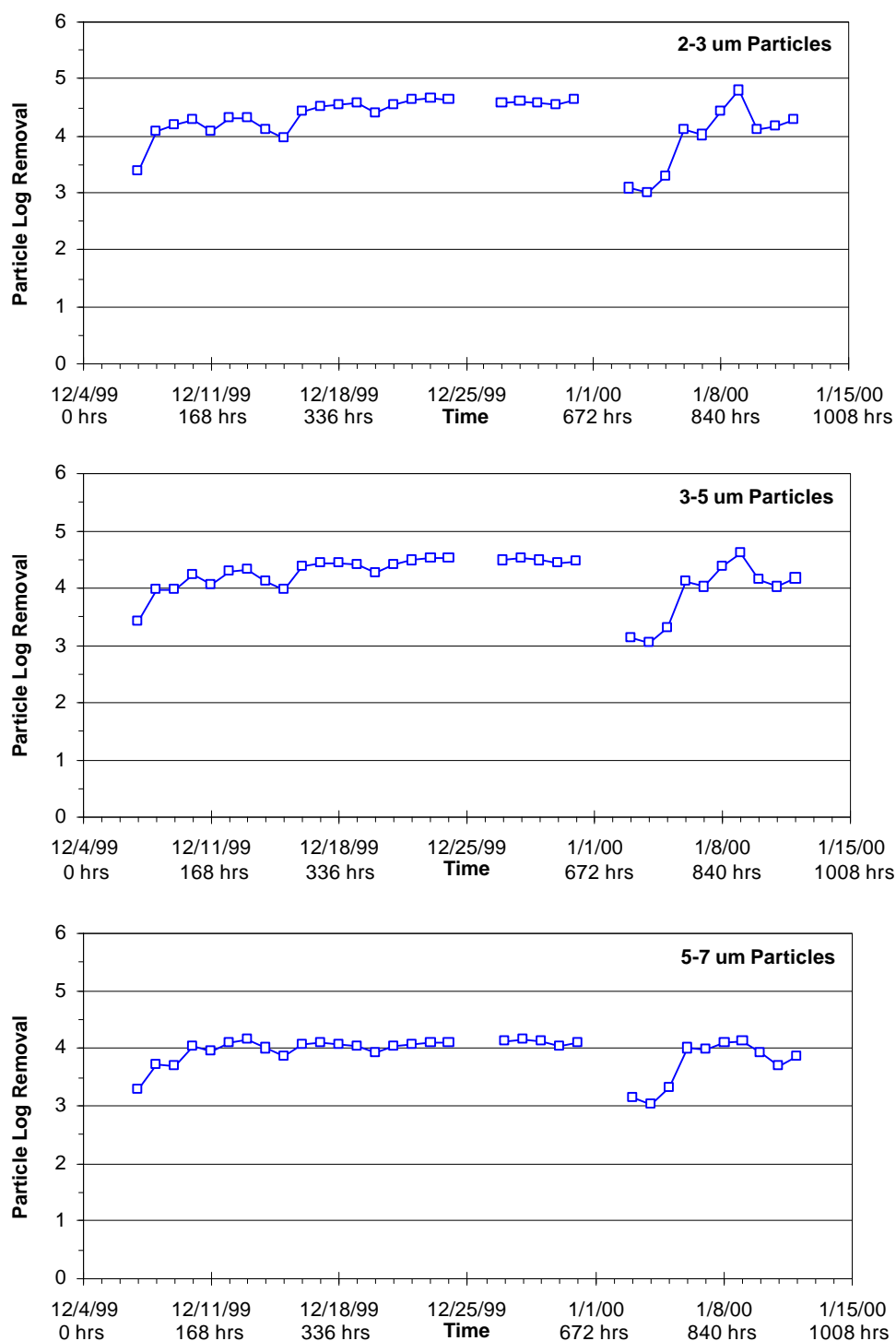
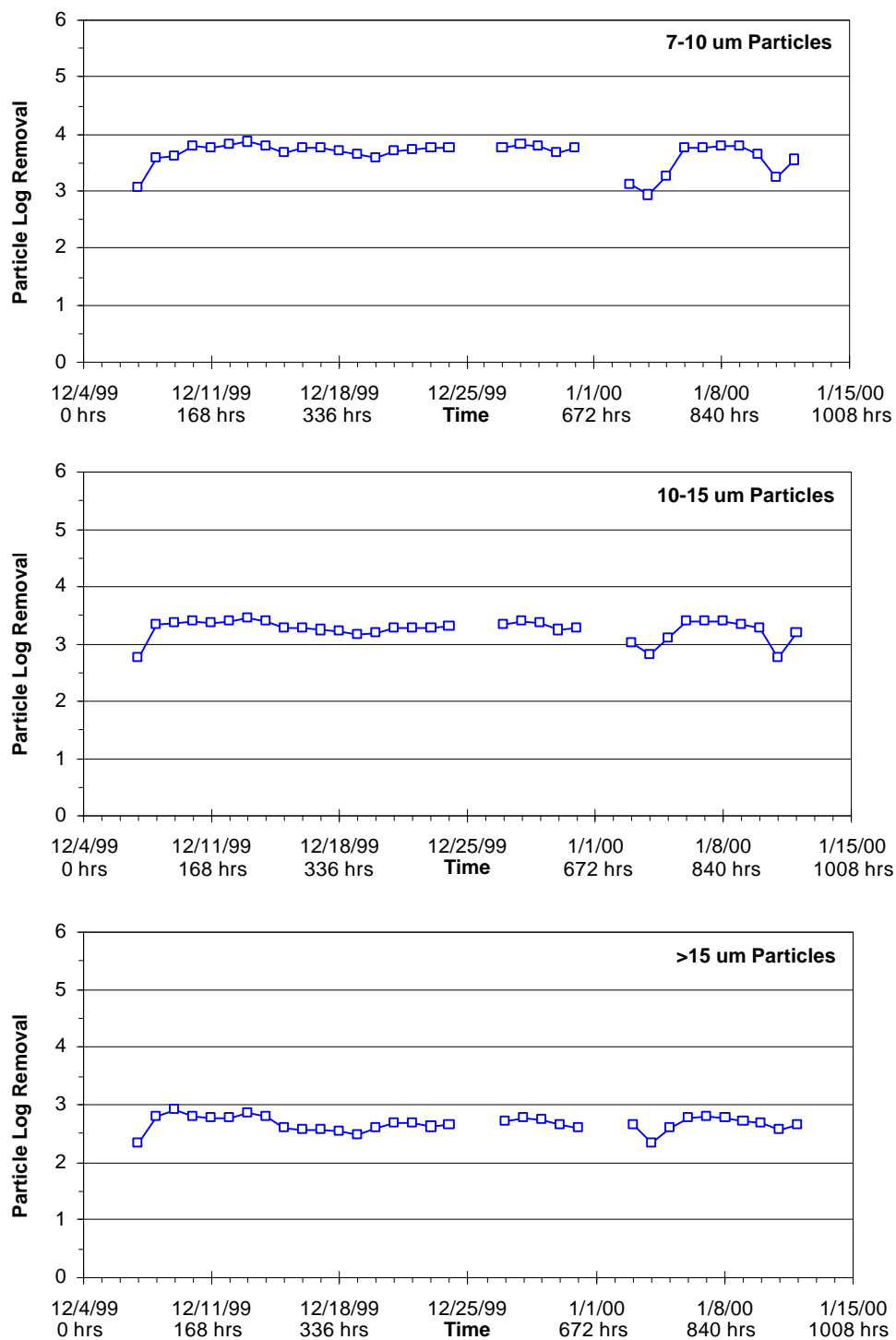


Figure 4-8. Continued.



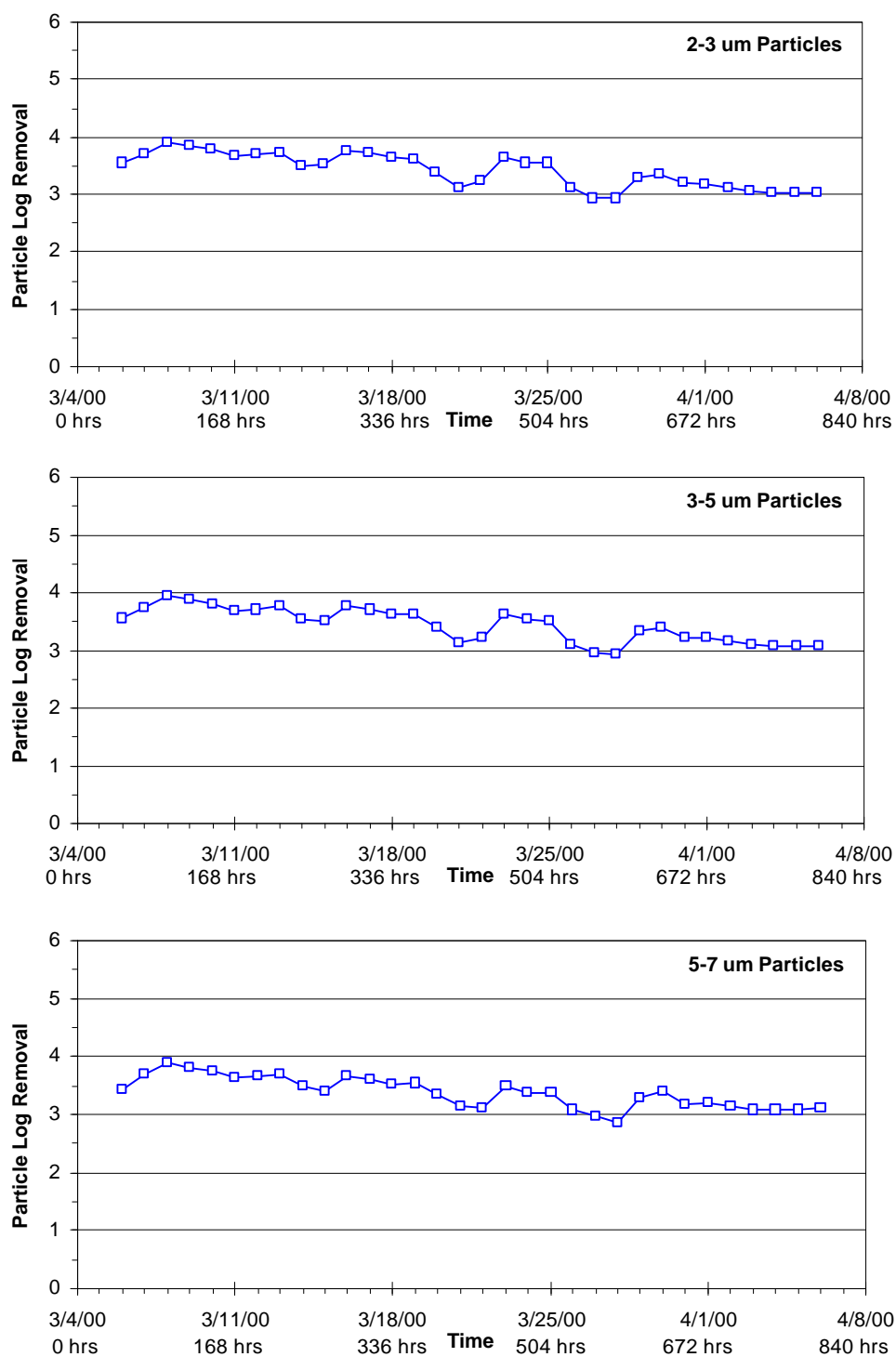
Note: Gap in data at 12/25/99 due to electrical outage of particle counters.  
Gap in data at 1/1/00 due to Y2K software failure.

**Figure 4-9. Particle removal for Ionics UF membrane system – Test Period 1.**



Note: Gap in data at 12/25/99 due to electrical outage of particle counters.  
 Gap in data at 1/1/00 due to Y2K software failure.

**Figure 4-9. Continued.**



**Figure 4-10. Particle removal for Ionics UF membrane system – Test Period 2.**

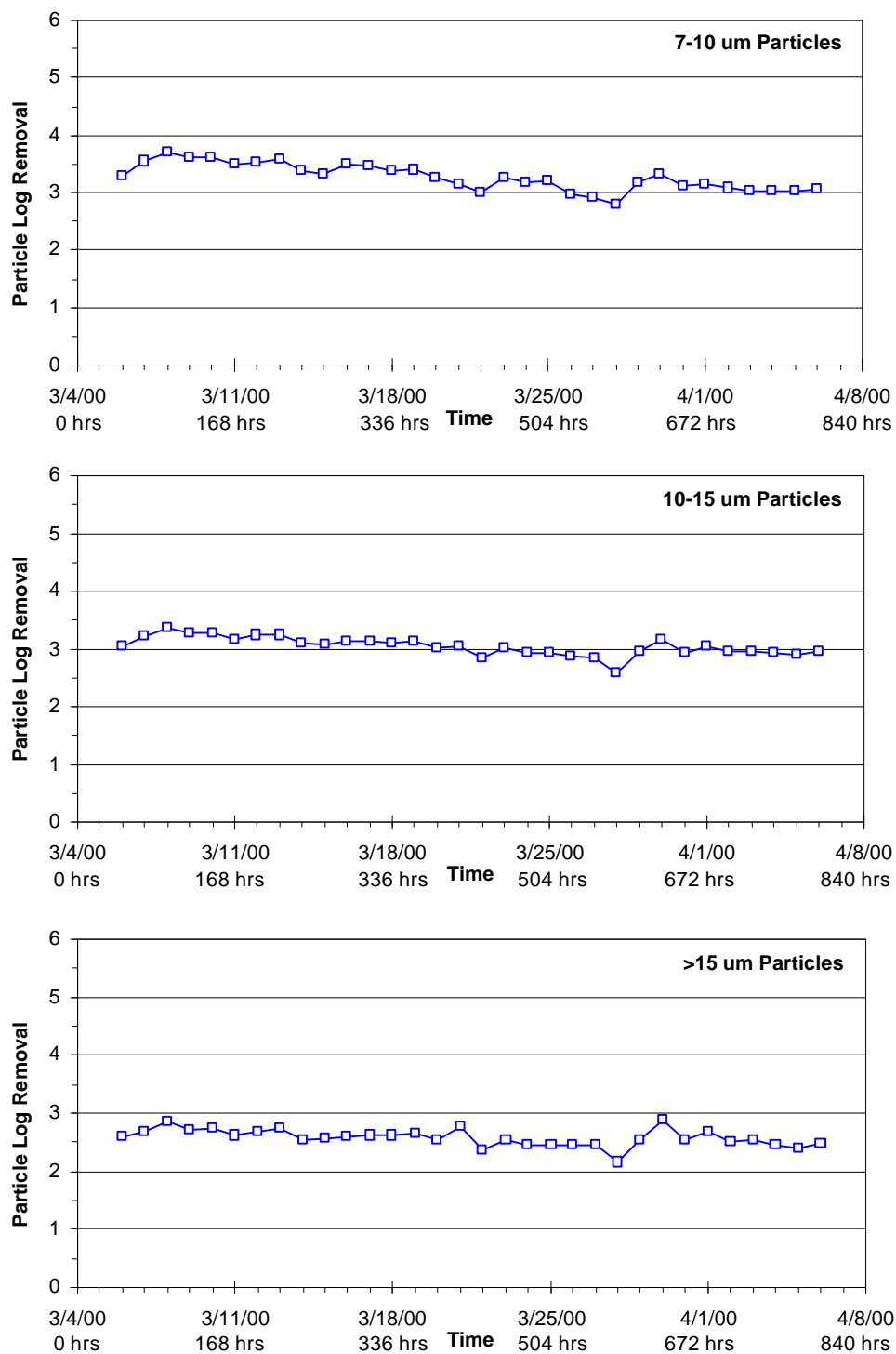
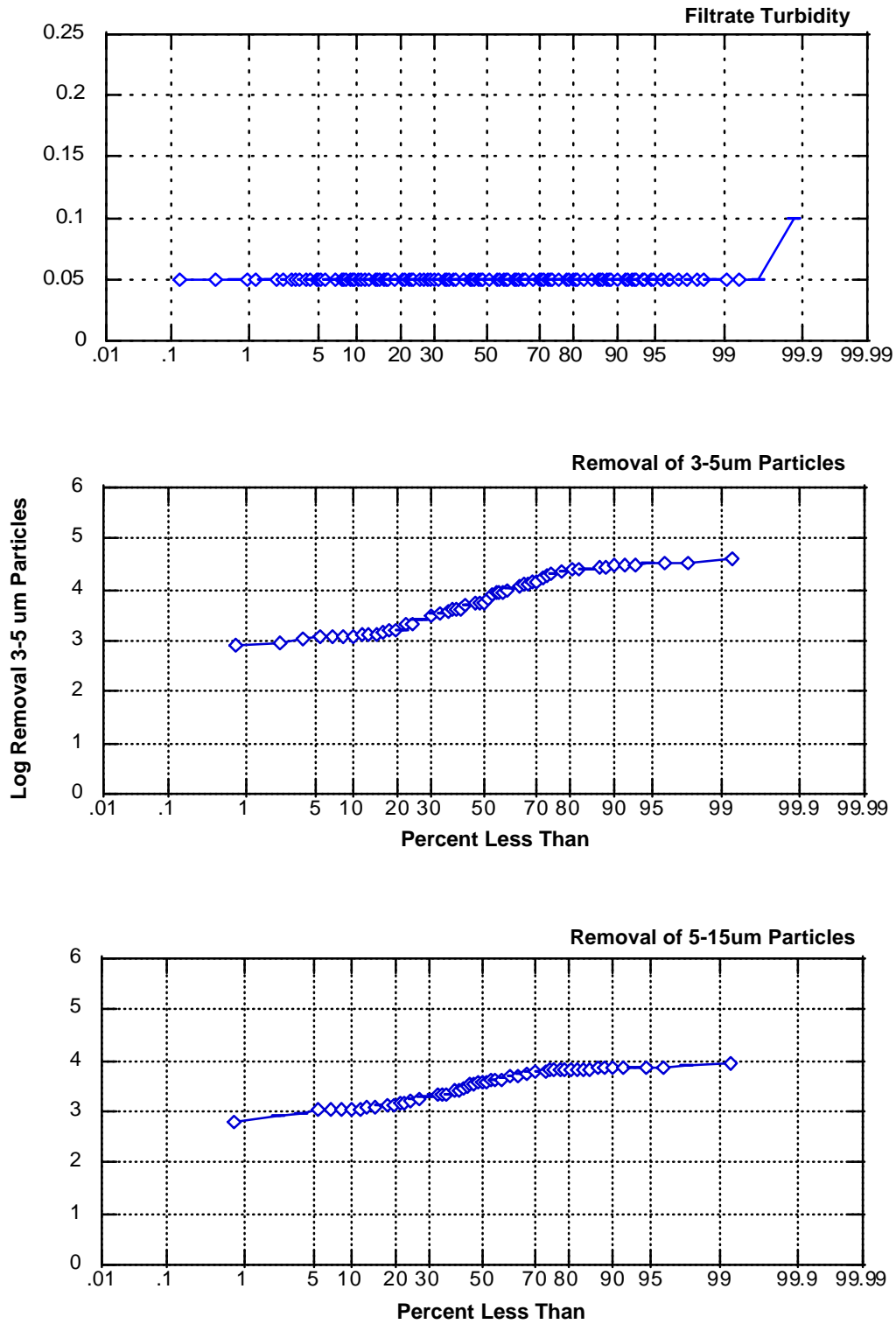
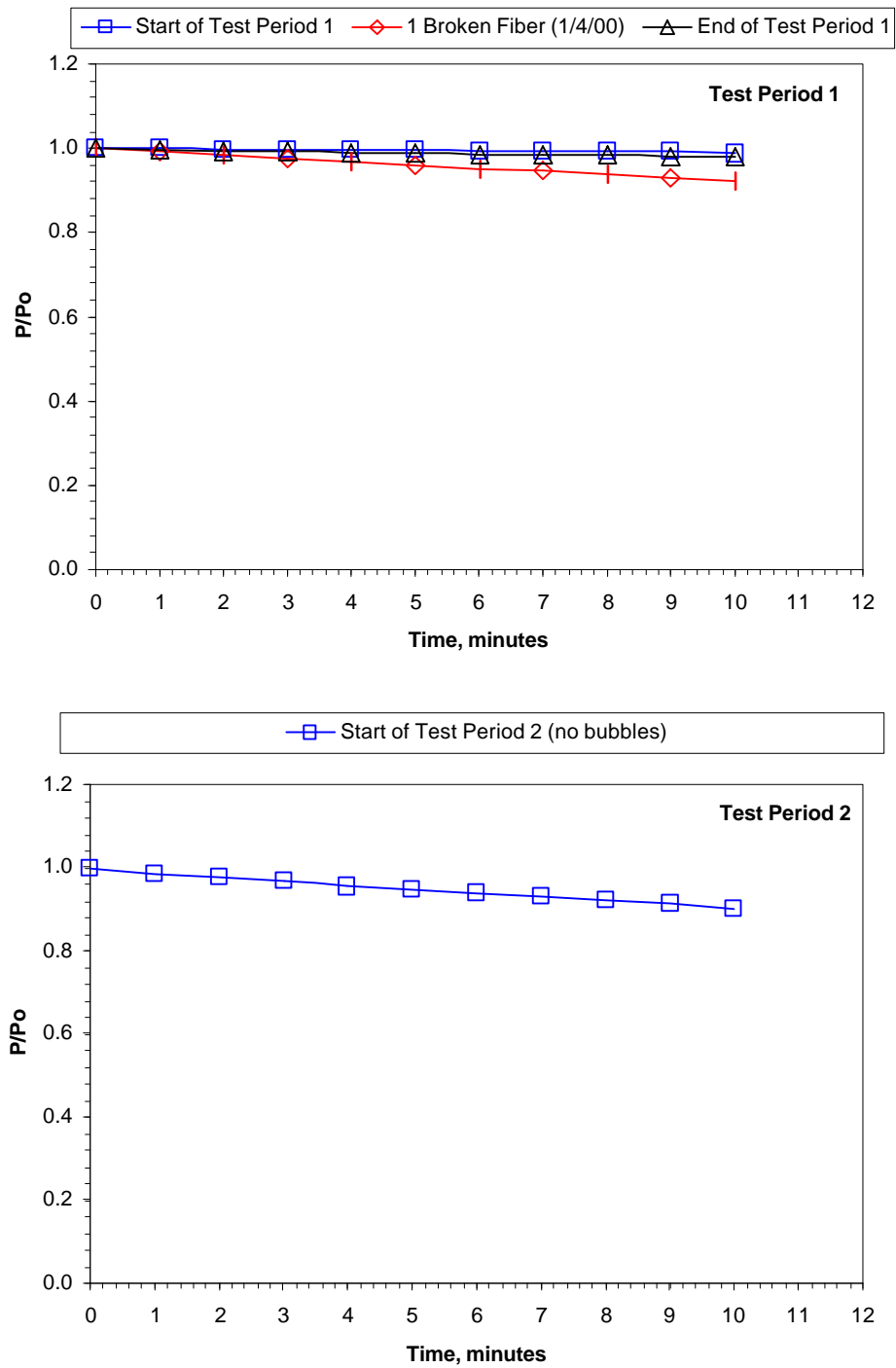


Figure 4-10. Continued.



**Figure 4-11. Probability plots of filtrate turbidity and log removal of particles for the Ionics UF membrane system.**



**Figure 4-12. Air pressure hold test results for the Ionics UF membrane system.**

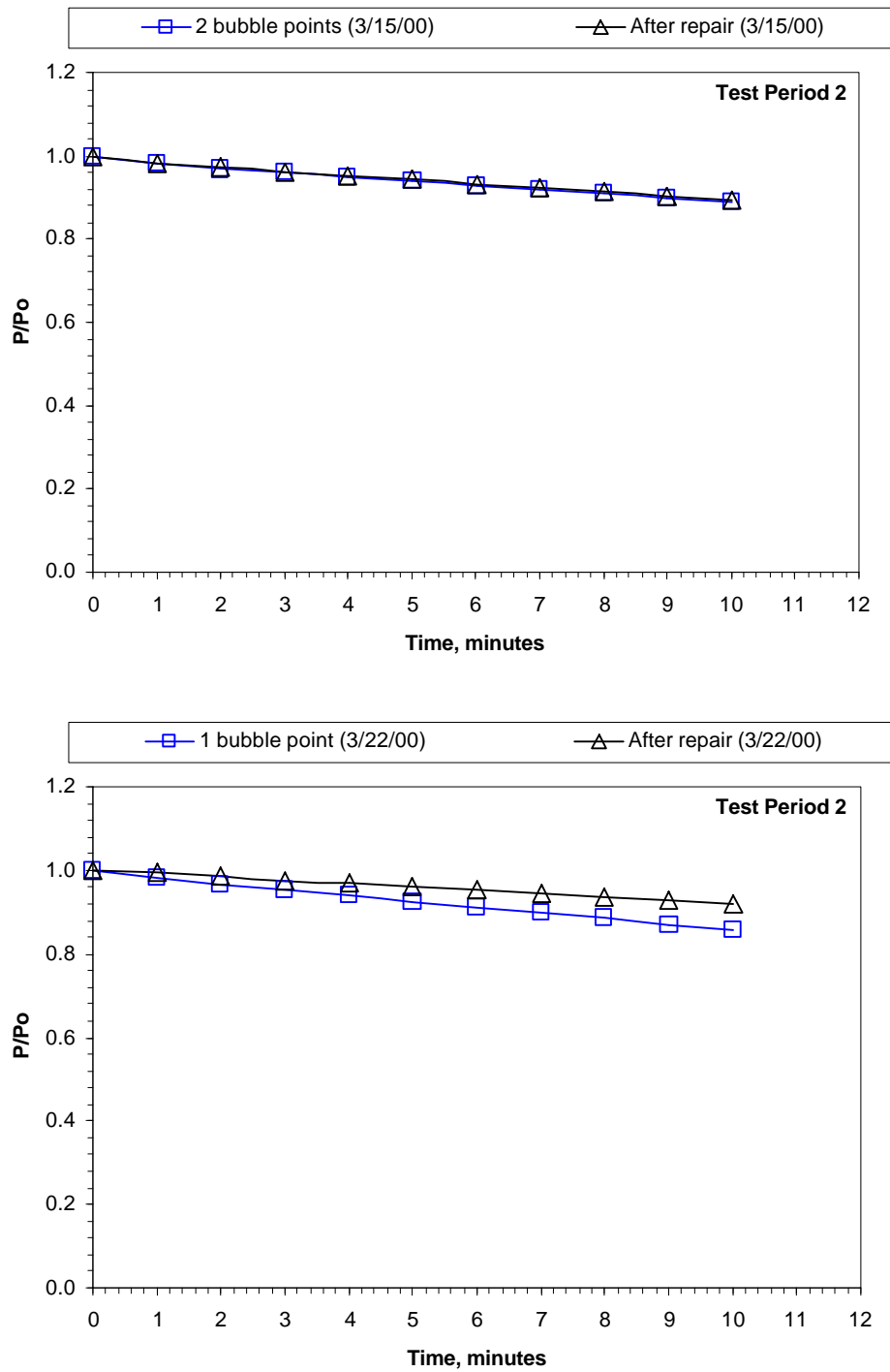


Figure 4-12. Continued.

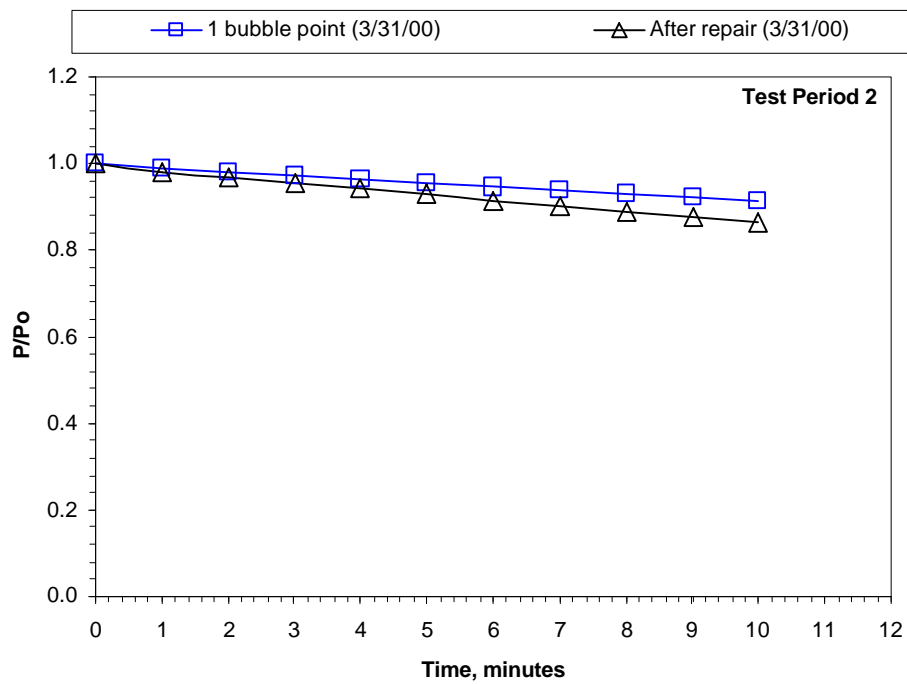
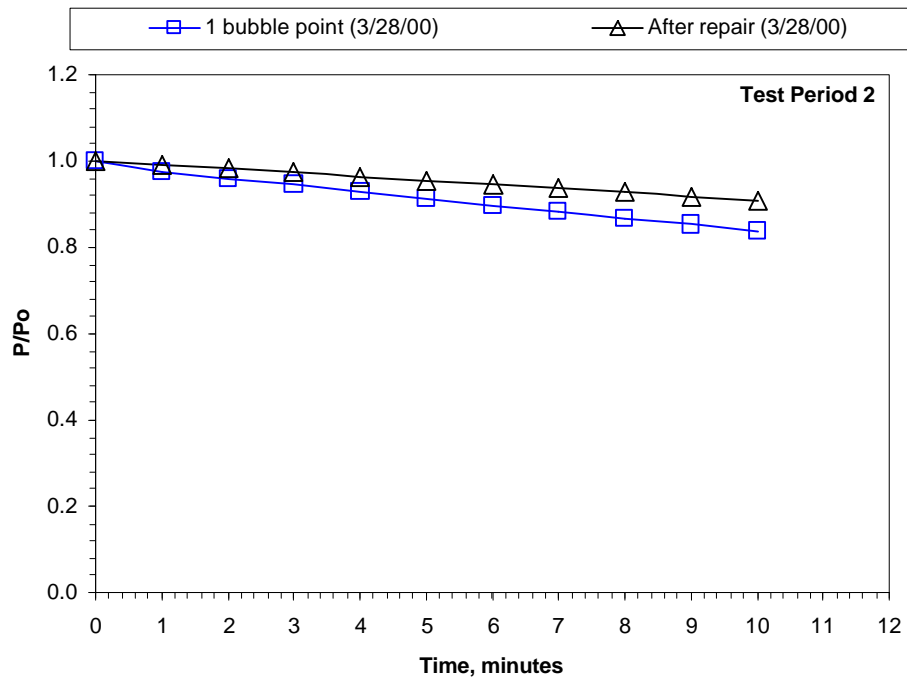
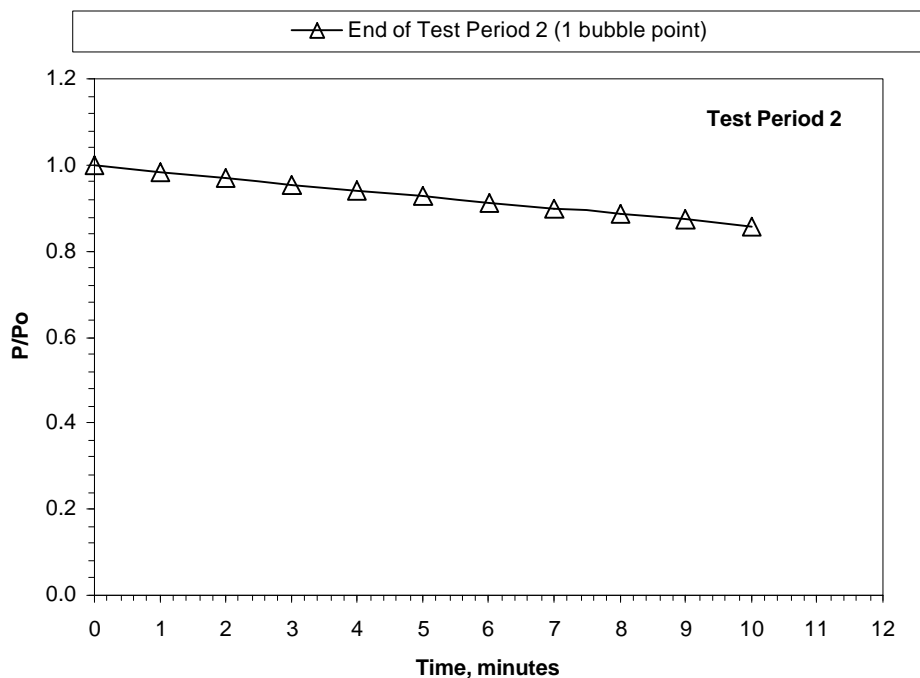


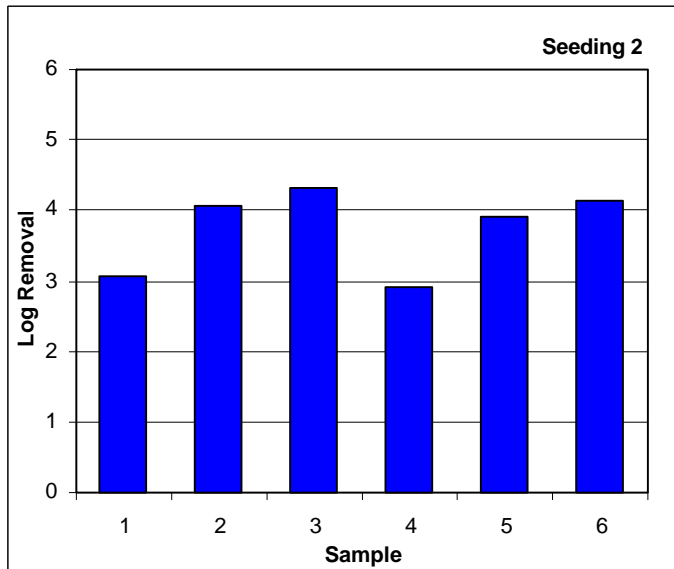
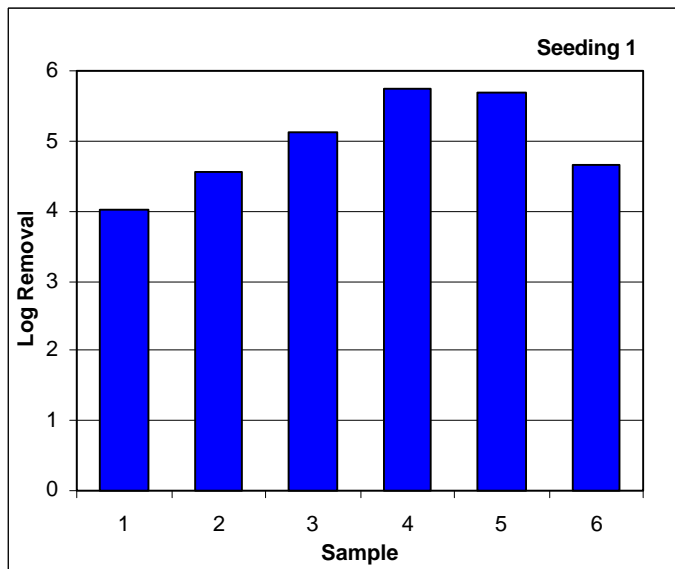
Figure 4-12. Continued.



**Figure 4-12. Continued.**

Seeding: Seeding 1  
 Date: 1/12/00  
 Specific Flux: 4.9 gfd/psi @ 20°C (119 L/hr m<sup>2</sup> bar)

Seeding 2  
 3/6/00  
 6.2 gfd/psi @ 20°C (152 L/hr m<sup>2</sup> bar)



**Figure 4-13. Log removal of seeded MS2 virus by Ionics UF membrane system.**

## **Appendix A**

## **Appendix B**

### **Raw Data Sheets**

**Appendix C**  
**Hardcopy Electronic Data**